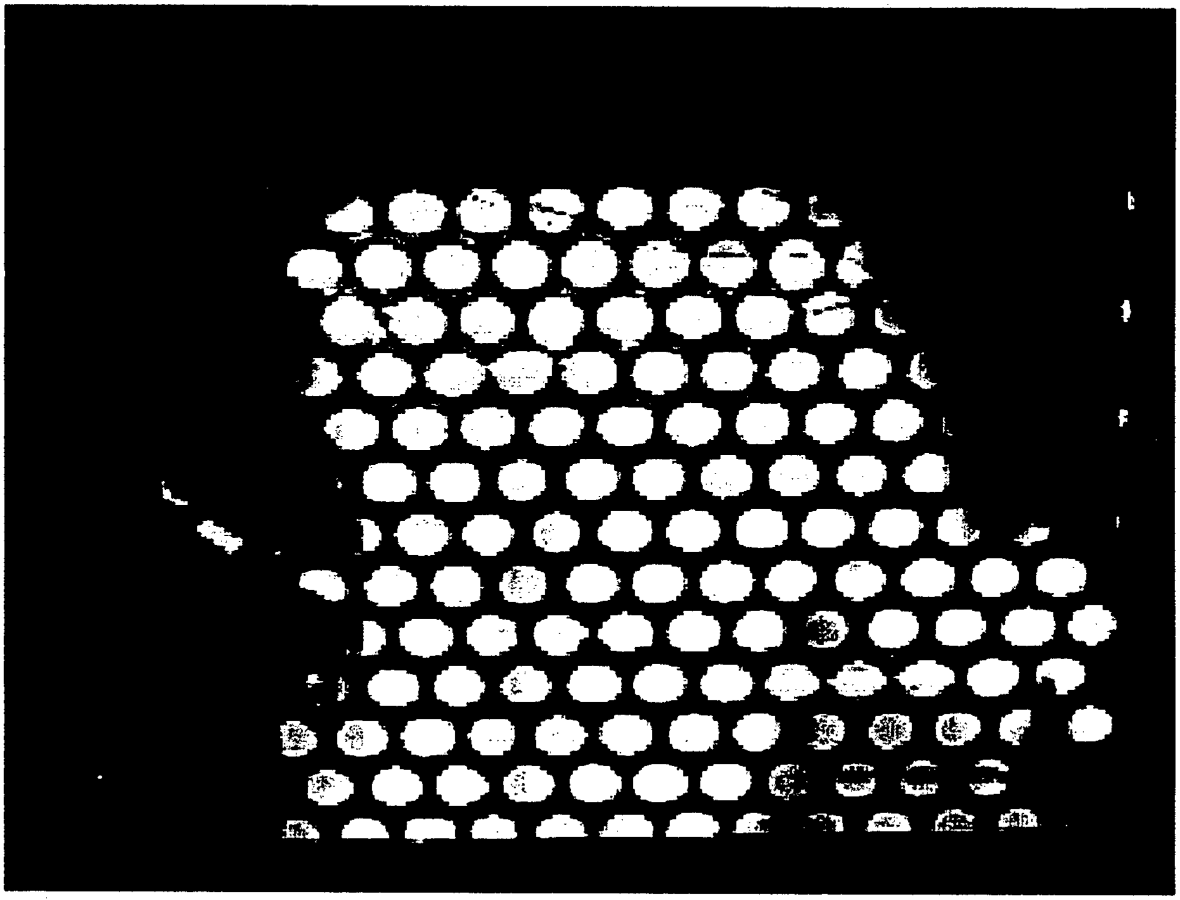
Microwave Production of Steady State Large Volume Air Plasmas



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13. ABSTRACT *(Maximum 200 words)* air plasmas can be created and sustained at atmospheric pressure at power levels of approximately 1kW/ cc , (1MW/ m^3) and these plasmas persist for hundreds of milliseconds after power is turned off. These plasmas can be made in an inexpensive and easy to build apparatus based around a microwave oven operating at approximately 1kW and 2.45GHz. These room air plasmas can also be made on large scale, using industrial microwaves at 915MHz at 30-75kW in an approximately ½ cubic meter nonresonant chamber. The plasmas in both cases appear to have electron densities of $10^{12}-10^{13}$ electrons per cubic centimeter and a gas temperature of 4000-5000K. Metastable molecular states may play a role in this phenomenon.

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Chapter 1

Microwave Production of Steady State, Large Volume Air Plasmas

Introduction and Executive Summary

At the beginning of our research program it was proposed to produce large volume plasmas in standard air, using microwaves as the power source. The program objective was the production of sustained air plasmas of several liters volume, in which the electron density exceeded 10^{12} electrons per cubic centimeter, and do this at a few kilowatts of power. The program would build on the recent successes of the Microwave ElectroThermal (MET) thruster demonstration program (1), which has successfully produced a plasma volume of about one liter. Under the proposed research effort, the MET technology would be extended to larger air volumes, using microwave power levels up to about 30 kW. This research was encouraged by the results of Powell and Finkelstien (2) Who were able to create luminous spheres, appearing to be plasmas, in room air using radio-frequency power at 30kW. Despite these previous accomplishments, many in the air chemistry and plasmas physics community were very skeptical that production of large air plasmas at atmospheric pressure and low power could be achieved.

It is the result of this research that the reports of Finkelstein and Powell have been strongly confirmed: air plasmas can be created and sustained at atmospheric pressure at power levels of approximately 1kW/ cc , (1MW/ m^3) a much lower than value than expected, based on experience with arc discharges, and further that these plasmas persist for hundreds of milliseconds after power is turned off. These plasmas can be made in an inexpensive and easy to build apparatus based around a microwave oven operating at approximately 1kW and 2.45GHz. It is a further result that these room air plasmas can be made on large scale, using industrial microwaves at 915MHz at 30-75kW in an approximately ½ cubic meter nonresonant chamber. The plasmas appear to have electron densities of $10^{12}-10^{13}$ electrons per cubic centimeter and a gas temperature of 4000-5000K. The best explanation for the existence and persistence of the PIA plasma appears, at present, to be large populations of metastable atoms or molecules that form in the heated air and act as an energy source to sustain ionization. This was the hypothesis of Powell and Finkelstein (2) and it still appears the best physical model.

Other Work and the PIA Hypothesis

A number of researchers (3,4,5) have used high frequency EM fields to produce large persistent discharges in air, which we will term PIA (Persistent Ionization in Air) plasmas as a simulation of the widely reported phenomenon called "ball lightning". This concept follows a theory formed by Kapitza (4) that ball lightning forms from RF waves in the atmosphere. The subject of ball lightning has a long and colorful history both of observations and investigation and are reviewed in (6,7) .

The earliest report of artificial creation of ball lightning is found in the notes of Tesla (7). Investigations by Powell and Finkelstein in the late 60's using 75Mhz RF at 20KW succeeded in making spherical discharges that would separate from the electrodes where they formed (2). It was found that the large volume plasmas produced in those experiments persisted for as much as one half second after power shut-off. These researchers used a 15 cm diameter Pyrex tube to form the plasmas. (Figure 1.1) In more recent experiments in Japan, researchers used a 1-5 kW, 2.45 GHz power source driving a resonant cavity, but did not restrict the physical extent of the plasmas formed . The researchers created large air discharges in the resonant cavity, but these discharges were often augmented by ordinary combustion. Other experimenters have used Helium gas as a plasma medium at atmospheric pressure (8).

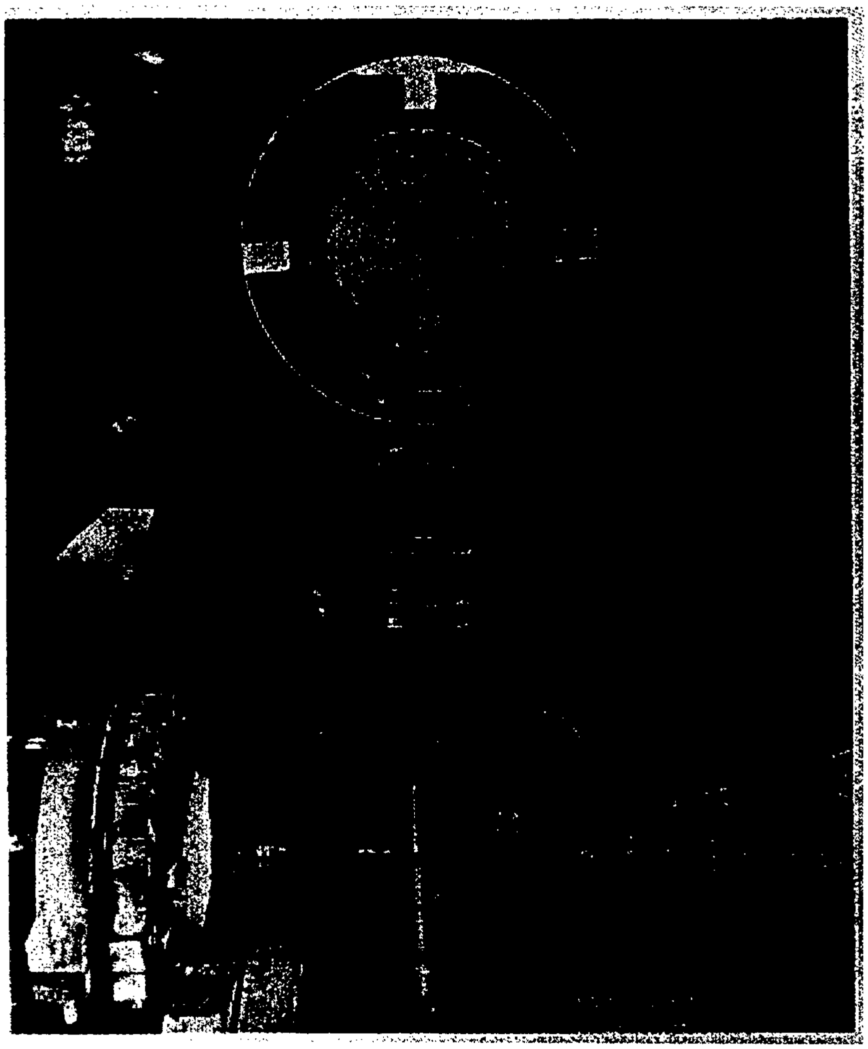


Figure 1.1 A PIA plasma created by Powell and Finkelstein using 75MHz,from (2).

In these previous experiments, either high power sources, resonant cavities or specialized gases were used to create large plasmas at atmospheric pressure. The present investigation employed a simple, easily constructed apparatus consisting of a modified 1000 W microwave oven, and succeeded in creating large plasmas at atmospheric pressure in ordinary air.

Therefore it seems reasonable to propose the hypothesis that some metastable behavior, widespread in diatomic or larger molecules- such as a vibrational mode, leads to persistent ionization in gases at atmospheric pressure. We will call this the PIA hypothesis.

Safety Considerations

It should be noted that the first detailed account of a ball lightning discharge in a laboratory, is the account of the death of a Russian lightning investigator (2). While this

discharge was created from a natural lightning power source, and obviously involved far more energy that those described in this research, it should be regarded as a cautionary tale. The plasmas of this type , both observed in nature and in the laboratory, appear to be capable of storing electrical and thermodynamic energy in dangerous amounts, and should therefore be created and studied with caution. In our own research it was also found that PIA plasmas are high temperature objects and can emit dangerous amounts of ultraviolet light, that can easily burn unprotected skin or eyes. In our experiments therefore, the plasmas and microwaves were almost always confined within the microwave chamber, and UV resistant goggles were always worn.

Persistent Ionization in Air : A General Perspective

The success of this experimental effort was not widely expected, plasmas formed in air are normally considered short lived and very energy intensive. Thus finding that PIA plasmas could be made and scaled easily was surprising to many.

Air is commonly considered a poor gas for the formation of discharges, because oxygen, water vapor, and to some degree nitrogen capture free electrons and immobilize them. The resulting negative ions then collide with positive ions and recombination occurs, making recombination more rapid than in an inert gas such as argon. By contrast, recombination in inert gases proceeds via direct capture of an electron by an ion, with the emission of radiation; however the cross section for this type of collision is small and this delays this process.

Recombination in air proceeds primarily through the capture of electrons by oxygen, forming negative ions, which then collide with positive ions at a collision frequency of approximately 10^9 sec^{-1}, to allow recombination. In this process the resulting neutral atoms and even third bodies carry away the energy of the recombination (9). This process can proceed more quickly than the direct radiative recombination of electrons and ions, which is inhibited by quantum mechanics. Free electrons in air thus are believed to be short lived compared to those in an inert gas, lasting only on the order of 10 microseconds. Given this property of air it would seem an unlikely medium for the production of large persistent plasmas. However , even before our success , it was found that air, under certain conditions, appears to support long-lived ionization.

The PIA hypothesis is an attempt to explain phenomena commonly observed in thunderstorms and oxygen in some laboratory experiments. In these instances air, and some other gases, are observed under certain conditions to have high levels of ionization for periods that are very long compared to conventional estimates of recombination times. The most common example of this phenomenon is during thunderstorms.

Lightning discharges remain fundamentally mysterious after decades of research, because in a thunderstorm, 10^6 V discharges commonly occur over 5 km distances, whereas in the laboratory such a potential can produce discharges over only 10 meters. Investigation has revealed that a poorly-understood process, termed the "stepped leader", forms the kilometers-long ionization channel before the visible lightning bolt occurs. The stepped leader apparently creates and

sustains ionization in air for periods of 30 ms before the main lightning discharge, which itself last a few microseconds.

The stepped leader is observed via high speed cameras to be a ball of light, approximately a meter in diameter, that darts down from the cloud in microsecond jumps of a few meters each, punctuated by pauses of tens of microseconds before jumping a few meters again (9). This process continues several kilometers to the ground and takes commonly 30 ms to be completed. During this period little light is observed as compared to the main discharge. The main, microsecond-long discharge of the lightning then occurs. This is followed by an interval of 10 to 100 milliseconds during which no activity occurs, followed by another microsecond-long discharge down the same path. This cycle can repeat many times. Despite the fact that recombination times in air, hastened by electron attachment to oxygen and water, are on the order of 10 microseconds, appreciable levels of ionization appear to precede the main lightning discharge by 10 ms and persist after it for periods of 10 ms or longer. The stepped leader phenomenon and the interval between discharges, which appear to last thousands of recombination times, are not understood (10), and yet are demonstrated in every lightning storm.

A partial physical rationale for this phenomenon is that in thunderstorms some type of ionization occurs that has a much longer lifetime in air than observed in conventional laboratory discharges, suggesting that mobile electrons are formed and sustained in some metastable regime of kinetic and potential energy. In this regime these electrons can move freely for periods much longer than normal recombination times, and their rate of loss of energy through collisions is low.

Evidence for such persistent ionization in pulsed dc and RF discharges produced in the laboratory has been reported (2, 11). Russian workers Minin and Baibulatov (11) reported persistent "afterglow" plasmas in air after the cutoff of 1 ms, 1 kA discharges. These afterglows persisted for 4 to 7 ms, and were found in air, N_2, and CO_2 but could not be seen in inert gases. The effect could not be seen at pressures below 0.3 atmospheres. Minin and Baibulatov reported the discharge behavior resembled that of a jet of water, in that it exhibited the formation of globules, a phenomenon normally associated with surface tension.

Persistent ionization has also been seen in RF discharges. Manwaring (2) reported 1 meter long cylindrical plasmas in air, formed in a large resonant chamber excited at 75 MHz. These plasmas persisted for 500 ms after the RF power was cut off. Powell and Finkelstein (2) continued this work at 75 MHz using a 30 kW source, and created plasmas between electrodes. These plasmas were observed to detach from the electrodes and persist in a drift tube away from the electrodes for 500 ms after the RF power was ended. Electron densities were measured to be $3 \cdot 10^{12}$ cm^{-3}, 100 ms after the RF power was cut off. This effect was seen in air , N_2 , O_2 ,and N_2O, at pressures between 3 and .5 atmospheres, but not at lower pressures. The effect could not be seen in CO_2 or argon. Line spectra of materials forming the electrodes were seen in the optical emissions of the plasmas. When easily vaporized metals were used for the electrodes, the plasmas would not persist. This suggests that employment of electrodeless discharge techniques might prolong the plasma lifetimes further.

DC electric fields of 1000 V/cm have also been observed to prolong the lifetime of the plasmas (2). These dc fields are near breakdown for air, and this suggests that the fields somehow replenish ionization. Both the laboratory reports and lightning studies are consistent with a long-lived active electron component in air, that persists for 10 ms or longer. Therefore, based on the time scales of lightning strikes, and the reports by several laboratory workers, the PIA hypothesis would seem to form a starting point and form the basis for experiments. If a PIA regime exists for electrons in air, then dense plasmas could be created and sustained in the laboratory for a fraction of the power which would otherwise be expected. If PIA electrons move with less energy loss and recombine more slowly than is normally expected in air, then re-ionization must occur at a lower rate, thereby reducing power requirements. The relative power requirements for plasmas with and without PIA are compared in the following calculations..

Assume the existence of PIA electrons with a lifetime $t_{PIA} = 10$ ms, and that the average energy to create an electron ion pair is U = 35 eV. The power per unit volume required to sustain a plasma of $n_e = 10^{15}$ cm^{-3} is

$$p = n_e \bullet U / t_{PIA} = 5 \text{ W-cm}^{-3},$$

or 0.5 kW per liter or 5W/cc. It can be seen that if the conventional electron attachment recombination time of t_{attach} of 10 microseconds is used in this calculation, and assuming that the radiative and thermal conduction loss mechanisms remain the same, then the power required to sustain such a plasma becomes 0.5 MW per liter or 500W/cc.

Thus, we could interpret both the low power required for sustaining the PIA plasma and its long life after power cutoff as stemming from a long recombination time. Such an effect would explain not only our success in making and scaling PIA plasma but also much other observed electrical effects in dense gases both in the laboratory and in the atmosphere.

Report Overview

In the remainder of this report we will first discuss our techniques for making and sustaining PIA plasma in using 2.45GHz microwaves at 1kW power levels in non-resonant cavities consisting of modified kitchen microwave ovens. This will be discussed in Chapter 2. It is in this inexpensive and simple apparatus that PIA plasma's basic characteristics could be studied. Scaling of PIA plasmas to low pressure in argon and CO (Carbon Monoxide) was also done as well as using CO laser induced breakdown to trigger PIA formation at low pressure. In Chapter 3 we will discuss the creation of electrodeless PIA plasmas in cylindrical resonant cavities at 1 kW and 2.45GHz and our success in eliminating field enhancing sharp points or UV sources by triggering such discharges by laser induced gas breakdown. We then demonstrated scaling of PIA plasmas in cylindrical resonant cavities by going to lower frequency and higher power, 30kW at 915MHz. Chapter 4 discusses the successful scaling of PIA plasmas in non-resonant cavities to

high powers and large size : 50kW and 14liters. A brief final chapter will summarize our results and will discuss promising areas for further research.

Chapter 2
PIA Plasmas at 2.45 GHz in Non-resonant Cavities: Initial Investigations

Materials and Methods

A 1000 W microwave oven operating at 2.45 GHz was used to produce an untuned microwave field in a microwave-sealed cavity. The cavity was 27 cm tall, 39 cm wide, and 37 cm deep. The turntable motor was removed, leaving a hole in the center of the floor, which allowed the insertion of a spark plug for use as a UV (ultra-violet) light source. A size 6, 1" long sheet metal screw was located 2.5 cm from the center of the spark plug to act as a microwave antenna. A Plexiglas tube 3 inches in diameter and 7 inches high was inserted in the cavity vertically to contain the plasma. Its axis was slightly offset from the axis the spark plug to create a small amount of vorticity. Finally, a 1/8" copper tube was inserted into the cavity to feed gas to the center of the spark plug to allow the introduction of various gases. Figures 2.1 and 2.2 show the plasma and Figure 2.3 shows a diagram of the apparatus.

The UV source was a Champion model DJ7Y chainsaw spark plug, clamped in place with a nut inside the cavity. It was energized using a 4000 V half-wave rectified power supply commonly available in microwave ovens. At atmospheric pressure, the E field required to break down a gas using 2.45 GHz microwaves is very high and depends inversely on gas pressure : approximately $E/P \cong 30{,}000\text{V}/(\text{cm-atmos})$, where E is the electric field strength and P is the atmospheric pressure in atmospheres. UV light photoionizes some of the gas near the microwave antenna, which lowers the E field required to break down the gas.

The production of plasmas using this apparatus requires a small amount of minor adjustment and trial and error. The microwave patterns in commercial ovens, as well as power output, exhibit some variability. We have found the newer 1000W output microwave ovens , with smaller volumes (< 1.5Cubic feet) to maximize power per cubic meter, to give the best results, and they are probably more able to tolerate abuse without damage. It should also be noted that the apparatus worked best after it was "burned in" by placing a brass scouring pad, which provided many sharp points to create field concentrations, near the sparkplug to initiate a few discharges. This had the effect of blackening some of the paint on the bottom of the oven and apparently providing current paths to ground for the discharges as they initiate. Applying sandpaper to the bottom of the oven may accelerate this effect.

Lifetime tests of the plasma after microwave cutoff were performed using a wire loop probe with a diode to measure microwave field intensity and an amplified photo-resistor circuit to measure visible light

output from the plasmas. The photo-resistor was attached to the outside of the microwave-shielded oven door, roughly level with the location of the center of the plasma (see Figure 2.3). As a result, the photo-resistor could observe a field of view no larger than the microwave cavity. To insure other light sources did not interfere with the photo-resistor output, a video camera was also used to image the plasma in the oven and confirmed that it was the only source of light over the period of its measured lifetime. The output of both was collected on the same digital oscilloscope (Tektronix model 2232) to show the time that the plasma continued to emit visible light after microwave cutoff. The microwave detector and optical signals were shielded from noise from the high voltage transformer, so only microwave and photo-resistor signals could arrive at the oscilloscope. A small neon lamp, placed in the chamber, was also used to measure the time interval between shutting off the microwave controls and the dissipation of microwave power from the cavity as a verification of the direct measurements. The lamp was powered by the microwave field picked up by its bare leads. A video camera with a frame rate of 60 Hz measured the light from the neon lamp, and showed that it faded after one frame, corresponding to 17 ms, while the plasma persisted for an average of twelve frames beyond extinction of the lamp, corresponding to 200 ms.

The plasma volume was measured by marking the Plexiglas tube with a scale along its length, and visually comparing plasma length to the marks. The plasma diameter was taken to be equal to the tube diameter, because the plasma completely filled the cross-section of the tube. The data were recorded when the plasma was in a well-developed, steady-state condition.

The fixed-position Langmuir probe was inserted into the side of the Plexiglas tube, at the approximate location of the center of the plasma. The probe consisted of a coaxial cable with the shielding grounded to the cavity walls and the center coaxial cable conductor extended using a 0.25 cm diameter brass rod. The rod was insulated from the shielding by a 0.6 cm diameter glass tube, and the cable shielding was extended using a 1 cm diameter brass tube. The glass tube was extended beyond the end of the brass shield rod, to near the center of the tube. The center conductor rod was extended beyond the end of the glass insulator tube, to the center of the plasma. A hole drilled in the side of the Plexiglas tube allowed the insertion of the brass tube shielding of the probe, and the center conductor rod extended radially into the center of the Plexiglas tube. The probe was then biased to +/- 60 volts DC, and the current drawn from the plasma was measured across a 1 MΩ resistor. This probe characteristic, taken point-by-point, was used to measure both electron density and temperature.

The Langmuir probe was also used as microwave antenna to measure microwave fields near and inside the plasma. In this mode, a microwave survey meter (Holiday Industries Inc. model 1501) was located outside the microwave chamber, where the Langmuir probe exited. It was used to measure microwave leakage along the probe.

Two issues appeared most important in our investigations. 1. What is the electron density in the PIA plasma in steady state 2. What is the neutral gas temperature.

The difficulty with PIA plasmas is that they occur in dense gas where collisions should be frequent, yet they display many attributes of a plasma with few collisions, such as retreating from the microwave source. Since our interpretation of probe measurements is highly dependent on models of probe behavior in a plasma of high collision frequency, we will instead emphasize the observed microwave screening.

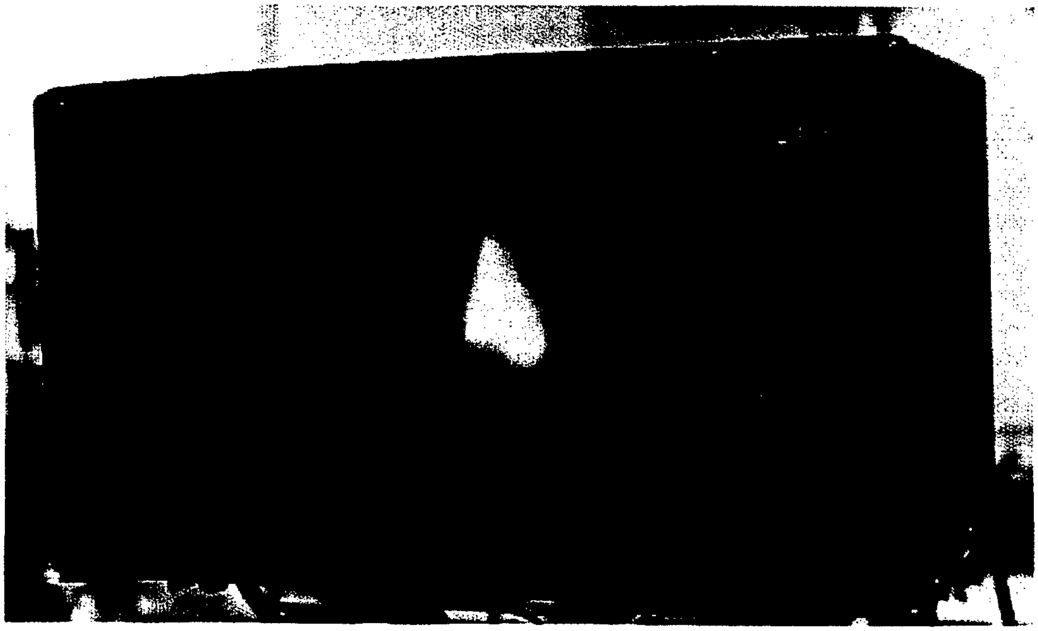


Figure 2.1 A PIA plasma generated in steady state in a conventional microwave oven.

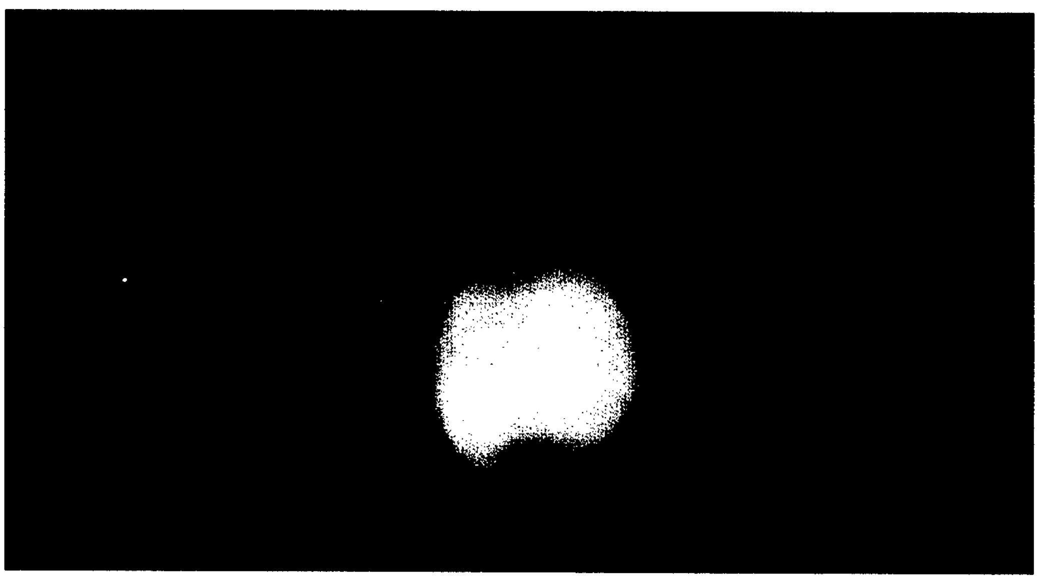


Figure 2.2 A PIA plasma inside a microwave oven, notice the evidence of toroidal structure.

Results

Four different gas mixtures were tried: ambient stagnant air, mixtures of air with argon, helium, and nitrogen. In these experiments the pure gases were introduced through the sparkplug and mixed with chamber air. All produced detached discharges. Argon-air was used for the Langmuir probe measurements because its lower ionization energy produced plasmas more repeatably. A low flow rate allowed the discharge to drift upwards through the tube, impacting with the top of the cavity like a liquid, and dissipate. The plasmas tended to be yellow-white in color, for all gases tried, though reddish or blue plasmas would occasionally be produced, apparently at random. A higher flow rate kept the plasma closer to the bottom, and a flow of approximately 1.2 LPM produced stable discharges filling much of the tube. This situation is shown in Figure 3 and 4. Experimentally, greatest success was achieved with the introduction of gas at low flow rates in such a way as to create a weak vorticity in the confining Plexiglas tube. The vorticity was due to the offset placement of the confining tube (see Figure 2), as mentioned in the Materials and Methods section. The vorticity, though mild, appeared vital to the PIA plasmas. Any attempt to center the confining tube on the gas inlet hindered plasma formation. In addition, a very high flow rate caused continuous arcing near the screw and spark plug, rather than formation of a detached plasma.

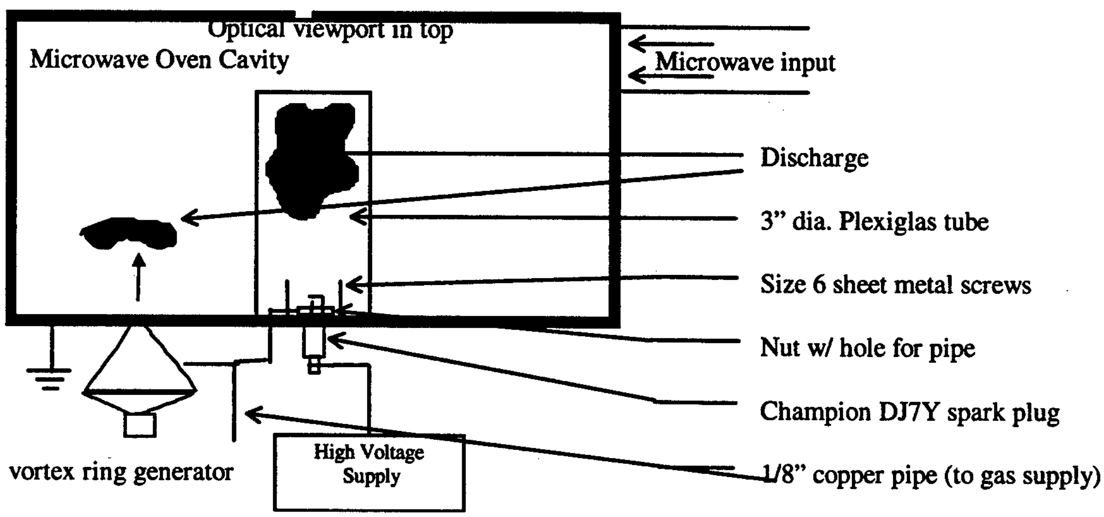


Figure 2.3 A diagram of a kitchen microwave oven modified to create and study PIA plasmas. Plasmas were trapped in a plexiglass or glass shroud, also it was found that toroidal plasmas could be formed by launching toroidal vortex rings of Argon into the chamber using a cone-plus-speaker vortex-ring generator.

Based on reports from previous investigators, and our own experience, a confinement of the plasma appears to increase its stability. Without the presence of a dielectric tube to confine the plasmas the device would sporadically produce free "fireballs", approximately 3cm in diameter, that would move about the chamber. Therefore, a 7.6 cm diameter Plexiglas tube, 26 cm long, was placed vertically in the cavity, resting on the cavity floor and surrounding the UV source, gas port, and antenna. A glass vessel was also used - a thin glass lamp shroud - and its flared shape resulted in larger volume plasmas. It should be noted that the PIA plasmas caused remarkably little heating of either the glass or Plexiglas tubes.

The plasmas were sharply defined, but turbulent. The basic form appeared to be nearly spherical but with an intense toroidal core (see Figure 2.2). To form them, the microwave field was first initiated, and then the UV source was turned on momentarily. That would cause a discharge near the antenna, which would form into an electrodeless globular plasma in the Plexiglas tube. The plasma would drift up to the metal top of the chamber if the flow rate was low, stand and move turbulently in the tube if the flow rate was around 1.2 LPM, or form a conventional looking arc attached to the antenna if the flow rate was much higher. The size measurements found that the plasmas had an average size of 280 cm^3 using an average argon flow rate of 1.2 LPM. The toroidal form could be used to induce reproduceable initiation by launching vortex rings from a cone attached to a audio speaker that produced vortex rings when the speaker was energized with DC. The cone was loaded full of argon gas and launched the vortex rings past the UV source and sharp point to create toroidal plasmas that would propagate upward to the roof of the microwave chamber.

Plasma Lifetime

Figure 2.4 shows a measurement of plasma emission using the photoresistor described in the Materials and Methods section during a stable discharge as microwave power was shut off. It should be noted that the microwave tube used in the experiments was operated using a 60 Hz half-wave rectified power supply, producing a 60 Hz duty cycle as shown in the results.

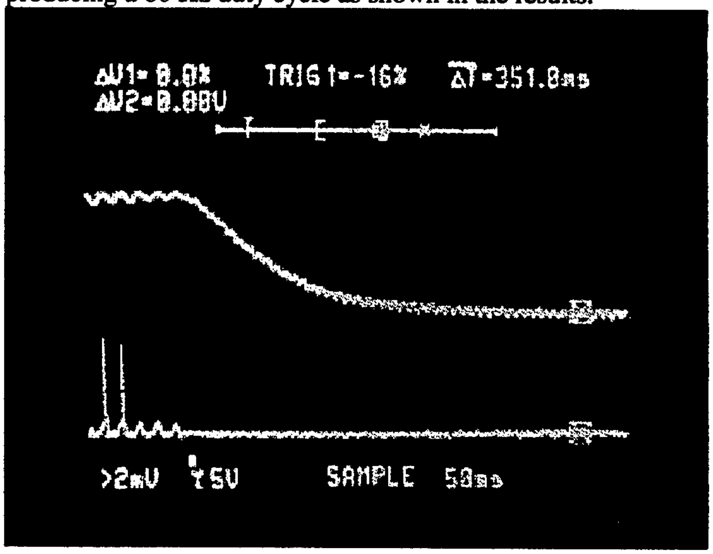


Figure 2.4 The decay of light emission from a PIA plasma in air (top curve) and the microwave signal (sharp spikes on bottom curve. Time divisions are 50ms each.

Plasma lifetime, loosely defined as three e-foldings of decay of optical emission amplitude, was found to be approximately 200 ms for stagnant ambient air, while the decay time to half-amplitude was 60 ms (see Figure 2.4). For argon, the lifetime was also 200 ms, and the half-amplitude decay time was 60 ms. This lifetime was also seen in video camera frames as the approximate time for which the plasma ceased to be visible, as described in the Materials and Methods section. The video camera, operating at a rate of 60 Hz, showed that the average argon lifetime was 12 frames after microwave shut-off, corresponding to 200 ms. The largest plasma volume, also measured by video camera, was 800 cm^3 using a flow rate of 1.0 LPM of argon.

These lifetime measurements are very similar to those measured by Powell and Finkelstein in 1971 (2) and shown in Figure 2.5

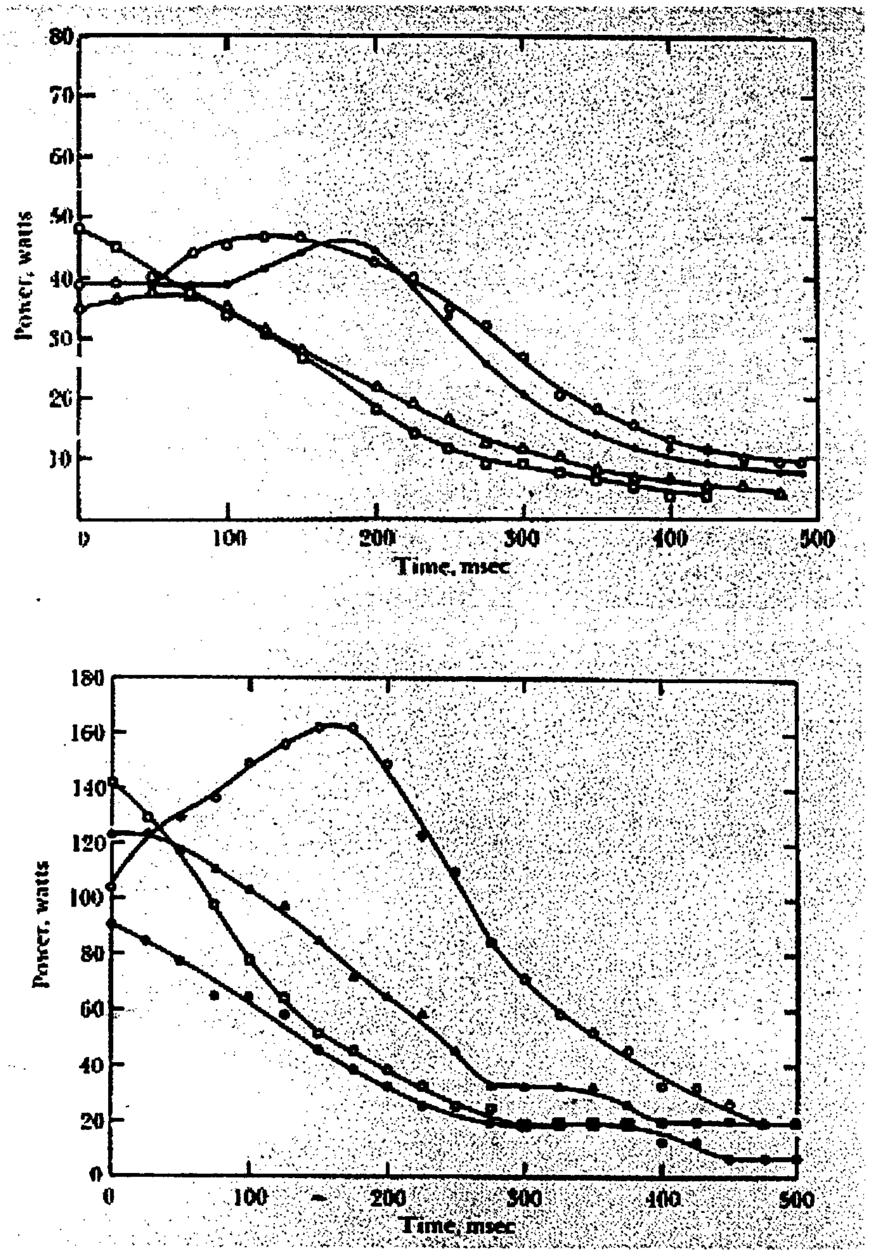


Figure 2.5 Time histories of plasma light emission after RF cutoff, as recorded by Powell and Finkelstein, note similarity to Figure 2.4.

Estimates of Electron Density

Estimates of electron density in the PIA plasma can be made based on its observed tendency to form roughly spherical bodies a few centimeters in diameter when moving freely and when confined to form bodies no thicker than a few centimeters, even when spaces larger than this were available. Since the PIA plasma seemed fairly uniform in luminosity the tendency to form bodies on the scale of a few centimeters indicates that self limiting behavior was occurring and that microwaves are excluded from plasmas thicker that a few centimeters. The PIA plasmas were thus growing until they began cutting off microwaves from their interiors, thus limiting further growth.. This self-limiting-of-size suggested the shielding length of the PIA was on the order of a centimeter. This estimate of effective shielding length was later confirmed by probe measurements in the plasma.

Due to the presence of the microwaves it was difficult to get Langmuir probe data so only three measurements were done, but these measurements were all near the maximum. . A maximum electron density of $n_e \cong 1.0 \times 10^{10}$ cm^{-3} was found at a 0.67 eV temperature using argon-air mixture at 1.0 LPM of argon, but these interpretations of Langmuir probe results are based on the assumption that the PIA plasma would behave as a collisionless plasma, but its neutral density is very high so it should be considered instead as a highly collisional plasma. This means that a Langmuir probe would not function in conventional manner, perhaps having sharp gradients in plasma parameters near its surface and thus its measurements were difficult to interpret.

Because it was difficult to ensure that the Langmuir probe was fully immersed in the plasma in each measurement, and to interpret its collected current data even if full immersion was achieved, it was utilized as an EM field diagnostic to estimate the plasma density. It was shown that the microwave leakage through the Langmuir probe output decreased below 0.5 mW/cm^2 while the plasma was surrounding the probe, but increased to over 5 mW/cm^2 when there was no plasma near the probe. It is this result, which utilizes the model of the Langmuir probe as a simple EM antenna rather than a current collector, and which then measures the shielding capacity of the plasma, which we consider to be physically unambiguous and subject to simple physical interpretation.

To interpret these results of the probe as an antenna we have used the theory of EM wave propagation into a conductive medium. Because the plasma is certain to be very collisional, we use an ohmic, rather than collisionless model of the plasma conductivity:

$$J = \sigma E$$

Where J is the electric current density, E is the local electric field, and σ is the plasma conductivity.

The conductivity can be formulated

$$\sigma = \frac{e^2 n_e}{m_e \nu_e} = \frac{4\pi e^2 n_e}{m_e} \frac{1}{4\pi \nu_e} = \frac{\omega_p^2}{4\pi \nu_e}$$

Where e is the electron charge, and m_e is the electron mass, and ν_e is the effective collision frequency of the electrons: the rate at which electrons "forget" the velocity acquired from the EM wave electric field due to interactions with other particles, and ω_p is the electron plasma frequency.

The problem of EM shielding by a plasma can be readily formulated in two limits: 1. In the limit of collision frequency being much less than the microwave frequency in which the microwaves will have the dispersion relation

$$k^2 c^2 = \omega^2 - \omega_p^2$$

In the limit of $\omega_p >> \omega$ we will have

$$k \cong {}^{i\omega_p}\!/_{c}$$

Which leads to a collisionless skin depth for the plasma, where fields are reduced 1/e,

$$\delta_o \cong {}^{c}\!/_{\omega_p}$$

However, if collisions are much more frequent than the frequency of the EM waves, something which we would expect in PIA plasma despite its collisionless behaviors, then we have the formula for the skin depth

$$\delta \cong {}^{c}\!/_{\sqrt{2\pi\omega\sigma}} = {}^{c}\!\Big/_{\sqrt{2\pi\omega \frac{\omega_p^2}{4\pi\nu_e}}} = {}^{c}\!/_{\omega_p}\sqrt{\frac{2\nu_e}{\omega}} = \delta_o\sqrt{\frac{2\nu_e}{\omega}}$$

Thus , for the case of very frequent collisions

$$\delta \cong \delta_o \sqrt{\frac{2\nu_e}{\omega}}$$

We can solve for the electron density by our observation that approximately two centimeters of plasma caused a ten-fold reduction of the microwave signal at 2.45GHz. This is is roughly $1/e^2$ or two e –foldings. Therefore , we can estimate the skin depth observed in our experiments as $\delta \cong 1$cm. We can thus write

$$n_e \cong \frac{1.1x10^{13}\ cm^{-3}}{(2\pi)^2}\left(\frac{2\nu_e}{\omega}\right) = 5.6x10^{11}\ cm^{-3}\left(\frac{\nu_e}{\omega}\right) = 8.9x10^{10}\ cm^{-3}\left(\frac{\nu_e}{f}\right)$$

Using the formula for the plasma frequency $\omega_p = 2\pi\,(9000\ n_e^{1/2})$ we obtain

$$1\ cm \cong \delta_o \sqrt{\frac{2\nu_e}{\omega}} = \frac{c}{\omega_p}\sqrt{\frac{2\nu_e}{\omega}}$$

Where ω=2πf is the microwave frequency of 2.45GHz. The collision frequency can be estimated as

$$\nu_e = \sigma_o n_o V_e$$

Where σ_o is the effective collision cross section in conventional low pressure discharges, normally considered to be $\sigma_o \cong 10^{-16}$, $n_o \cong 3 \times 10^{19}$ is the neutral number density at room pressure, and $V_e \cong 7x10^6$ cm-sec^{-1} is the thermal velocity for electrons at approximately $W_e \cong$0.5eV. This gives a value of $\nu_e \cong$ 20 GHz. However, in high temperature gases, the effective size of atoms and molecules expands, because of electronic excitation, (7) thus the effective collision rate, should be considered to be much higher, perhaps by a factor of 10 or more. Thus the effective collision frequency can be estimated as $\nu_e \cong$ 200 GHz. This means that the electron density must be approximately

$$n_e \cong 8.9x10^{10}\left(\frac{\nu_e}{f}\right) \cong 7x10^{12}\, cm^{-3}$$

Or , more realistically, the free electron density is estimated to be in the range $n_e \cong 10^{12} - 10^{13}\ cm^{-3}$.

In any case the electron density estimate is approximate due to the difficulty in calculating an effective collision frequency in the heated air and scales linearly with these calculations, however, any estimate of electron density based on electrical measurements must also make similar assumptions about collisions. Therefore, given that the electron density measurement is based on a simple interpretation of a simple measurement , we consider it to be fairly reliable.

All measurements of electron density are indirect in any electromagnetic measurement of a plasma, since what is really being measured is plasma current, either directly or indirectly. In a collisional plasma of collisional frequency much higher than the probing EM field the electron density and collision frequency are convoluted with each other in any measurement of current. Therefore the conductivity may be a better measure of plasma properties in collisional plasmas, since it requires no assumption about collision frequency, other than that is much higher than the EM wave interacting with the plasma. Measured this way we obtain , using $\delta \cong 1$cm ,

$$\sigma \cong \frac{c^2}{2\pi\omega\delta^2} = \frac{9x10^{20}\, cm^2/\sec^2}{9.7x10^{10}\, cm^2/\sec} \cong 9x10^9 \sec^{-1} \quad or \quad 1 mho\ /m$$

Or approximately the same as germanium. Thus, PIA can be viewed is a semiconductor.

Neutral Gas Temperature Estimates

In the case of neutral gas temperature estimates we have the advantage of a good working relationship with Stanford University where spectral measurements and their interpretation have been worked on for many years. Workers at Stanford made direct measurements of important spectra emitted from the PIA plasma, using a PIA generating apparatus we had delivered to them, and also gave us valuable advice on performing and interpreting our own spectral measurements.

Spectra of the optical emission from the PIA plasmas formed by Argon- air mixtures, done at Stanford University, show strong lines for atomic O and CN with a strong continuum background. The CN molecule is normally formed by low temperature thermal breakdown of CO_2 and N_2 and is a very strong radiator. Argon lines were not visible in the scan and this could indicate low neutral temperatures , below 5000K .

The best spectral fit to both the atomic oxygen and CN lines (Figure 2.6 and 2.7) indicates approximately 4000K.

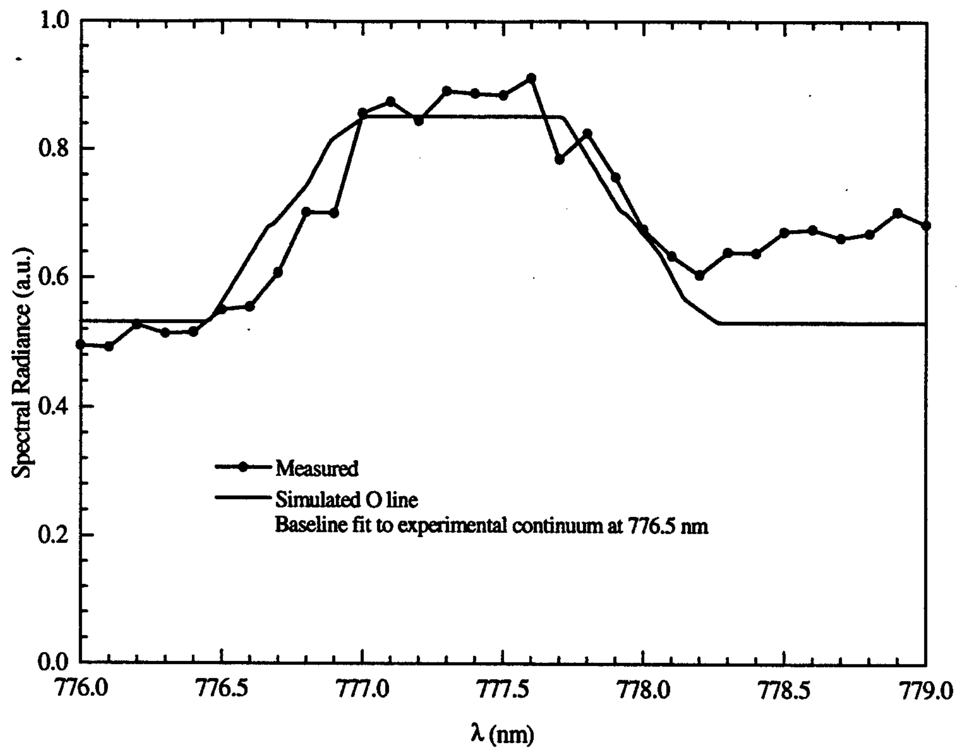


Figure 2.5. Measured emission spectrum exhibiting the 777.4 nm atomic oxygen line. Note the intense underlying continuum.

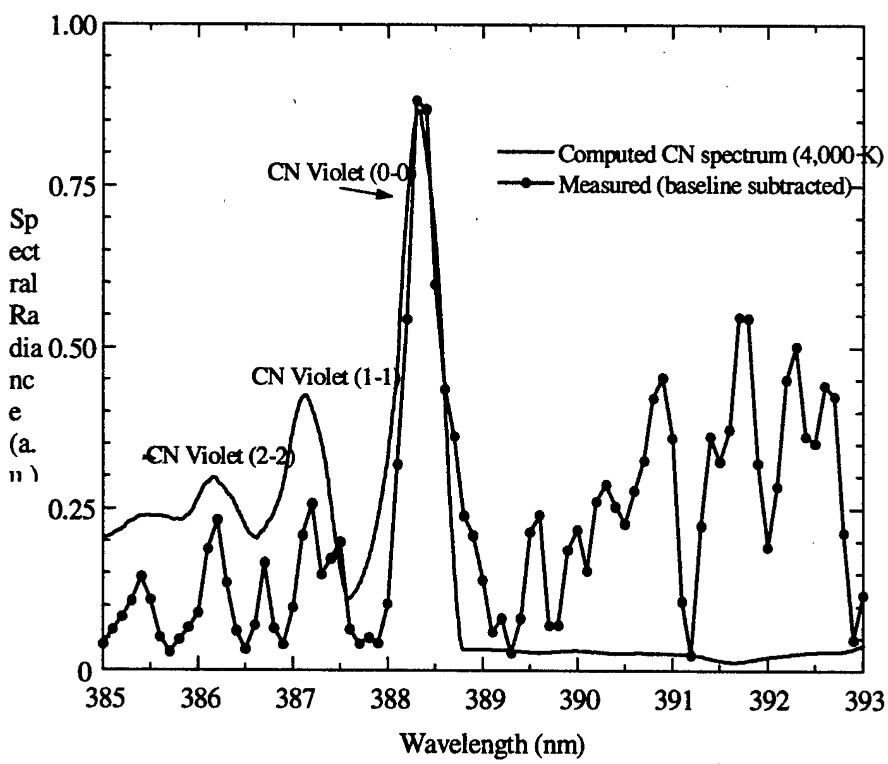


Figure 2.6 Measured emission spectrum exhibiting the 0-0 band of the CN violet transition

Additional estimates of neutral gas temperature were obtained at RSI by measuring the ratio of two lines in the OH (hydroxl radical) spectrum in the near UV. These measurements were made on a microwave oven PIA plasma using an Ocean Optics PC 2000 spectrometer and compared with a spectrum modeled supplied by Stanford University. The model spectrum in shown below (Figure 2.7)

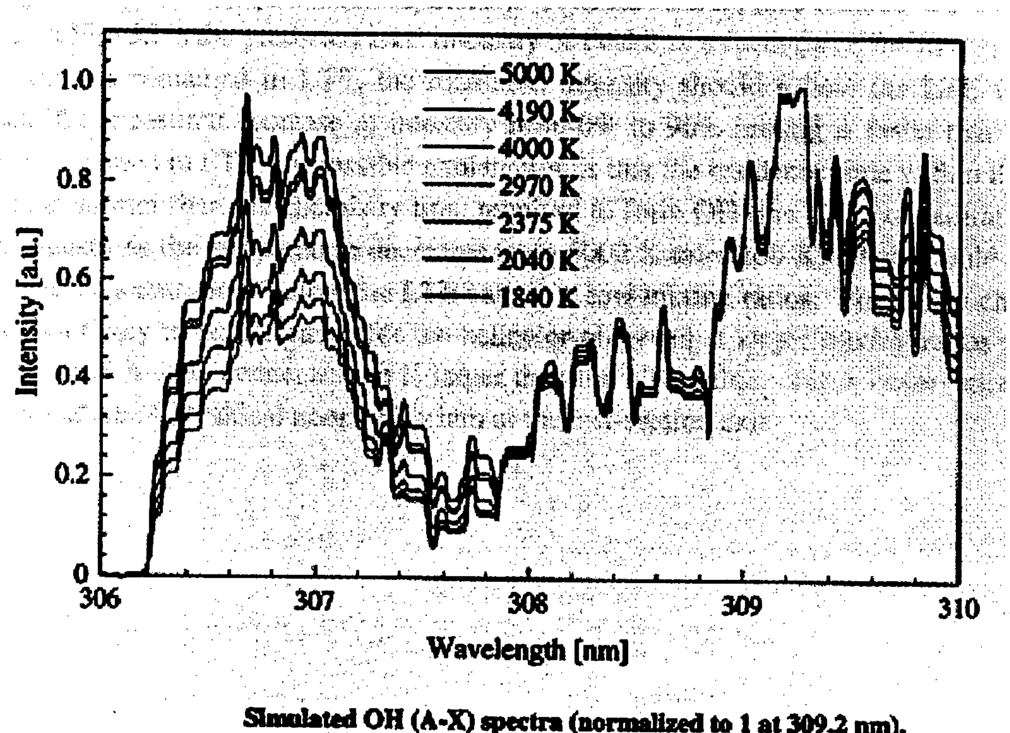


Figure 2.7 Spectrum of heated air between 306 and 310 nm generated by Stanford University.

The acquired spectrum is shown below in Figure 2.8 and 2.9 and confirms a temperature of approximately 5000K. The spectra were acquired from a standard microwave oven plasma using an air optical line of sight made through the top of the oven chamber (see Figure 2.3) The two spectra are of air with 1 LPM flowing argon injected with and with out the argon being bubbled through water, as can be seen the water had no effect on the PIA plasma temperature. The water did, however, appear to inhibit the PIA formation, making it harder to ignite. Once PIA plasma formed however, no change in size or stability was noted , except for a slightly more bluish appearance to the plasma in the tests made.

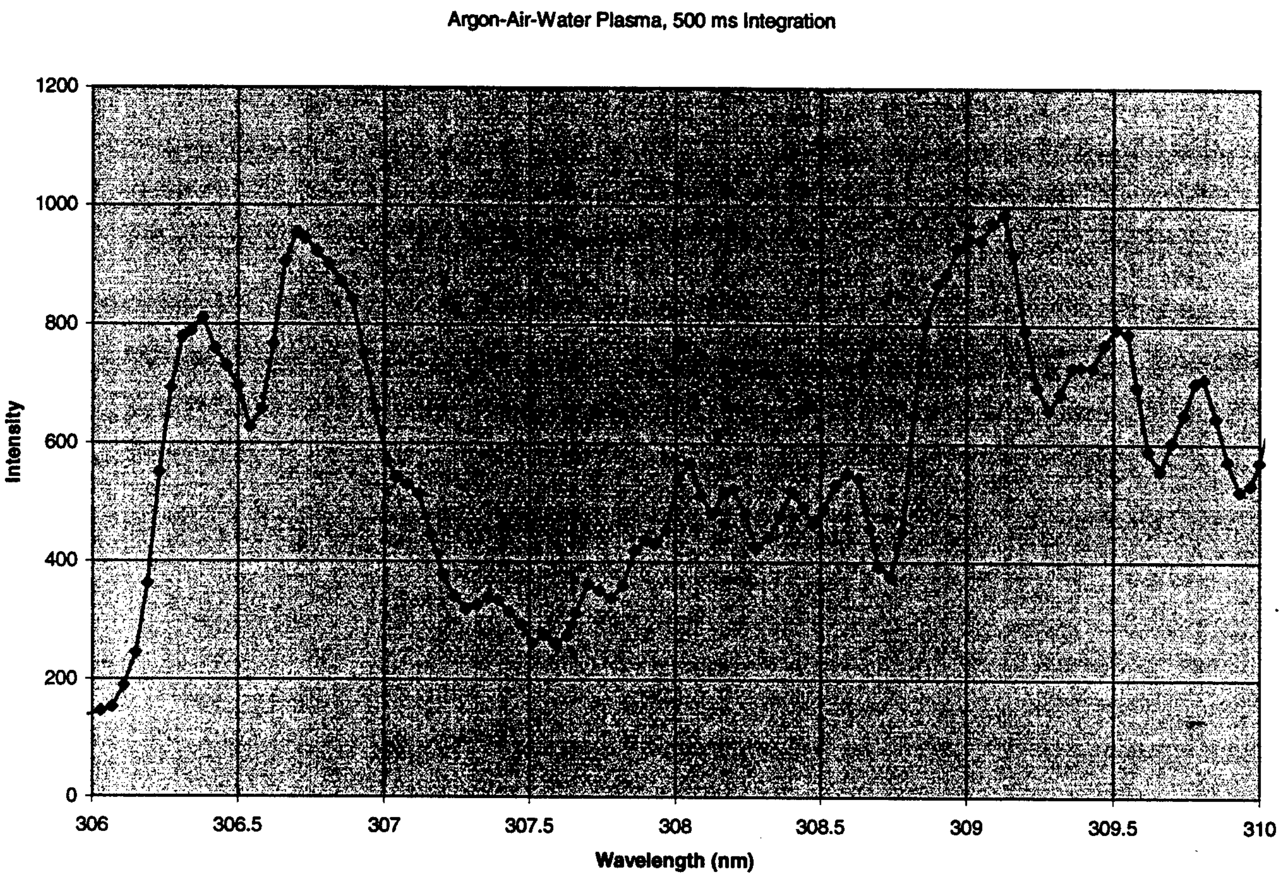


Figure 2.8 An experimental spectrum for PIA in air with argon mixture, with argon bubbled through water. Intensity of the lines was higher than for the dry argon case.

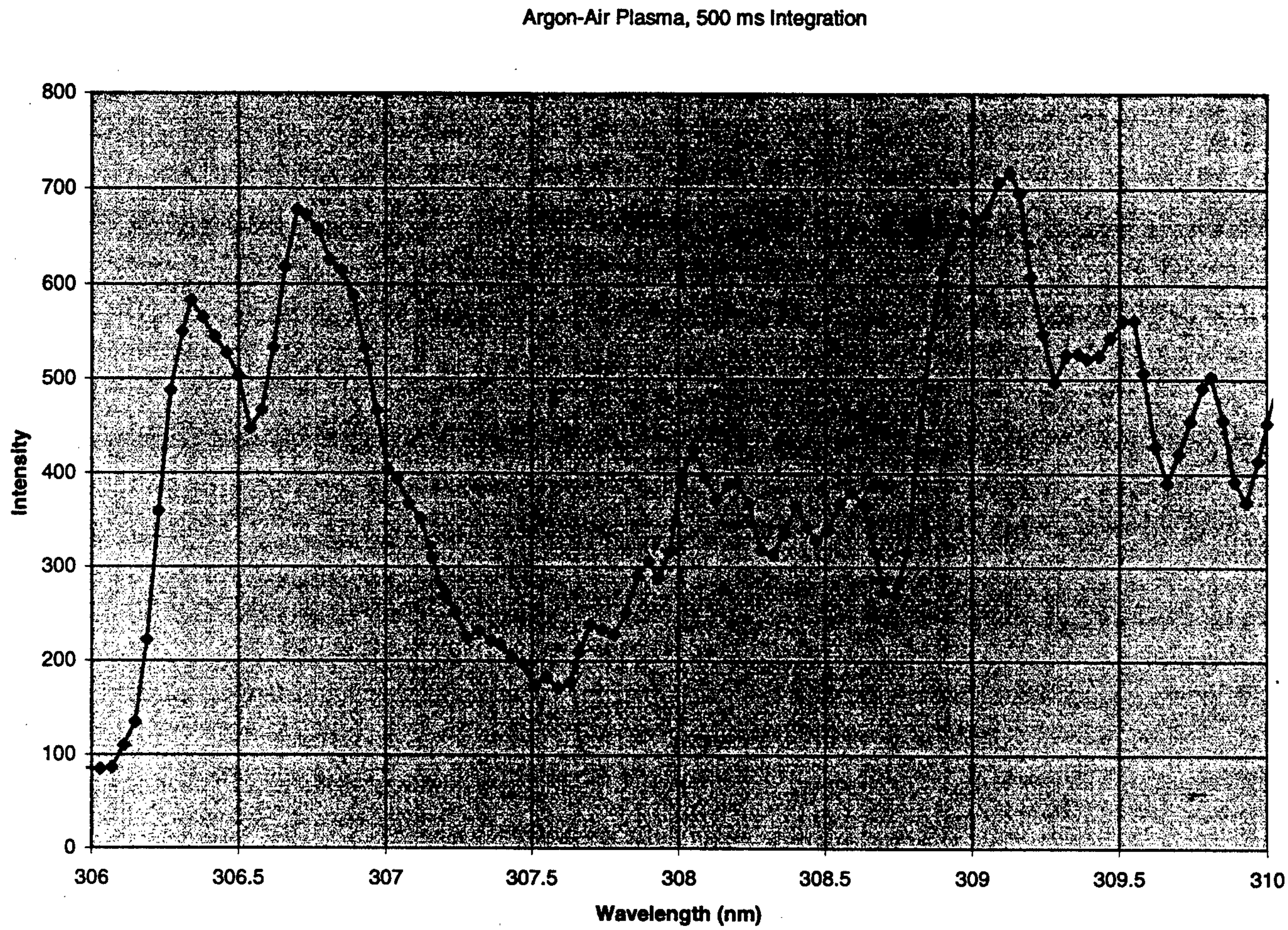


Figure 2.9 An experimental spectrum for PIA in air with argon mixture, with dry argon . Note the similarity to Figure 2.8 , indicating that the addition of water vapor had no effect on the OH lines.

Low Pressure Experiments

In order to facilitate collaboration with Bill Rich and his colleagues at Ohio State University, an apparatus was constructed to allow PIA plasma to be made in a sealed optically accessible cell , into which CO (carbon Monoxide) gas could be safely introduced, and optical diagnostics and even CO laser light could have a clear optical path. The apparatus developed is shown in diagram form below in Figure 2.10. Optical access to the microwave cavity was obtained by use of ¾ inch metal tubes, two feet long, which penetrated the cavity walls, but which formed below cutoff waveguides for the 2.45 GHz microwaves. Thus clear optical access and line sight was provided for the cell in the microwave chamber but the microwaves were unable to propagate down the pipes. Thus , safe , easy optical access was afforded to the cell down the pipes. The results of a study of the plasma formation in the cell at various pressures and with and without laser induced breakdown is seen in Figure 2.11. In general the PIA plasma tends to form at high pressures, above 25 Torr, as a sort of "second glow discharge mode" , separated form the normal glow discharge mode at a few Torr by a filamentary discharge regime. The neutral gas temperature, measured using C_2 rotational bands at 100Torr, the highest pressure that could be measured before the plasma became optically thick at the useful wavelengths, was approximately 1500K , considerably lower than the 4000-5000K neutral gas temperature measured for PIA at full atmospheric pressure. This suggests that collisional coupling between the electrons and neutrals is important in PIA, as would be expected if it was highly collisional.

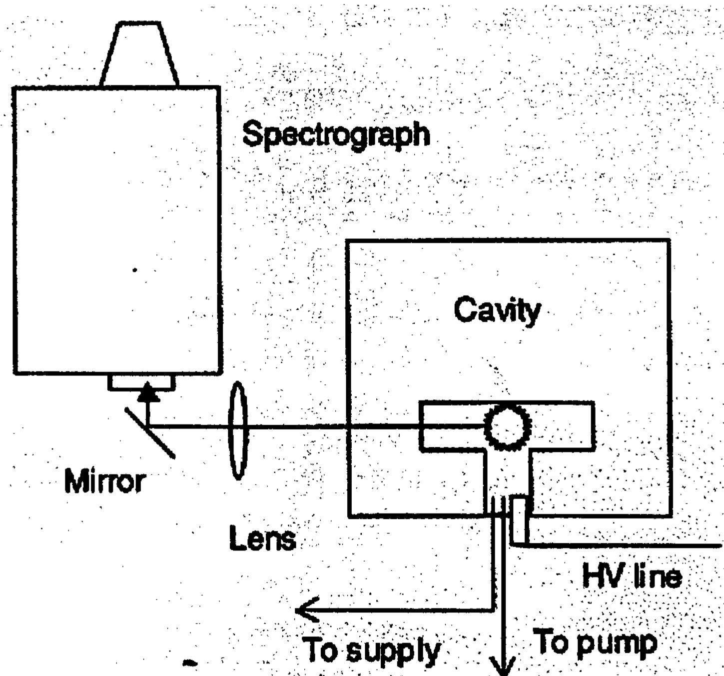


Figure 2.10 A diagram of apparatus, designed and built at RSI, for use at in collaboration with Ohio State University.

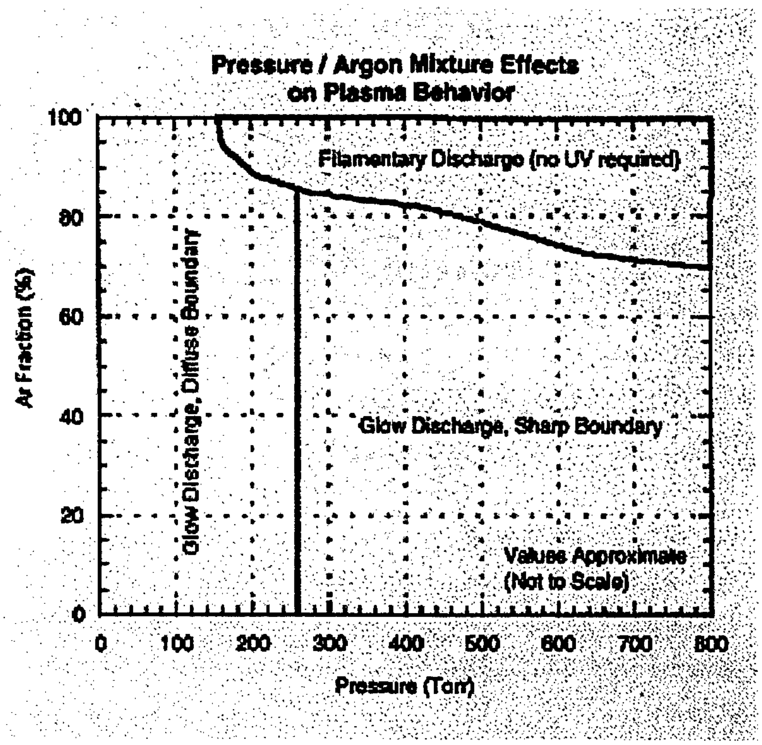


Figure 2.11 A graph showing PIA discharge phenomenological regimes as pressure was varied. Data collected with cooperation from Ohio State University

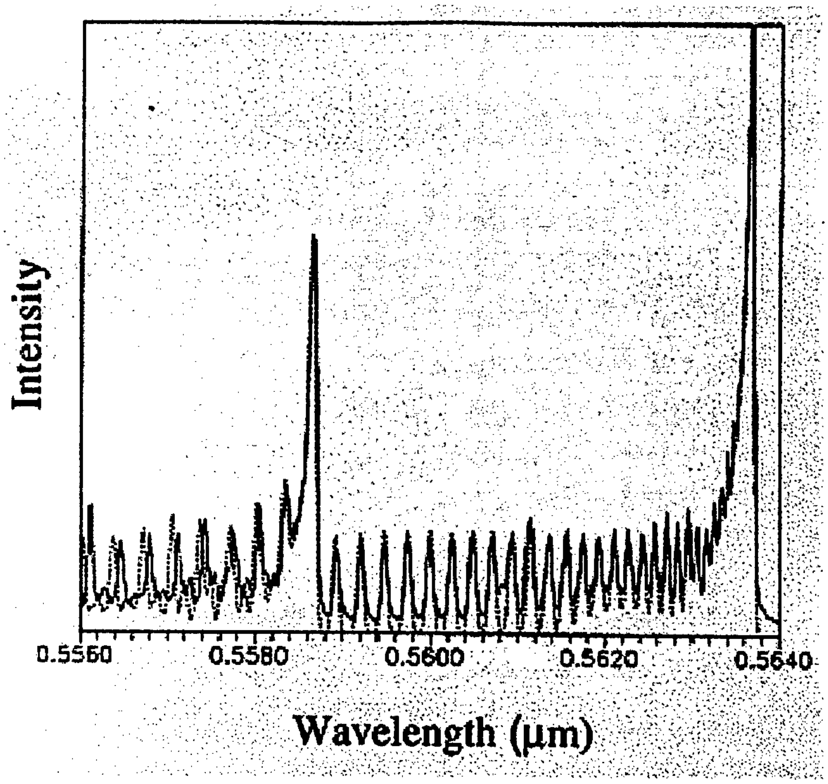


Figure 2.12 An experimental spectrum obtained in a PIA plasma at 100 Torr at Ohio State and fit to a model spectrum (dotted lines). The gas temperature appears to be 1500K.

It was found that even for an assumption of low electron density (critical density for a collisionless plasma): $n_e = 10^{10}$-10^{11}, the plasma ionization level was much higher than that predicted by standard equilibrium models for the measured temperature of 1500K. Ionization level more resembled temperatures of 3000K as shown below in Figure 2.13 , produced by Ohio State.

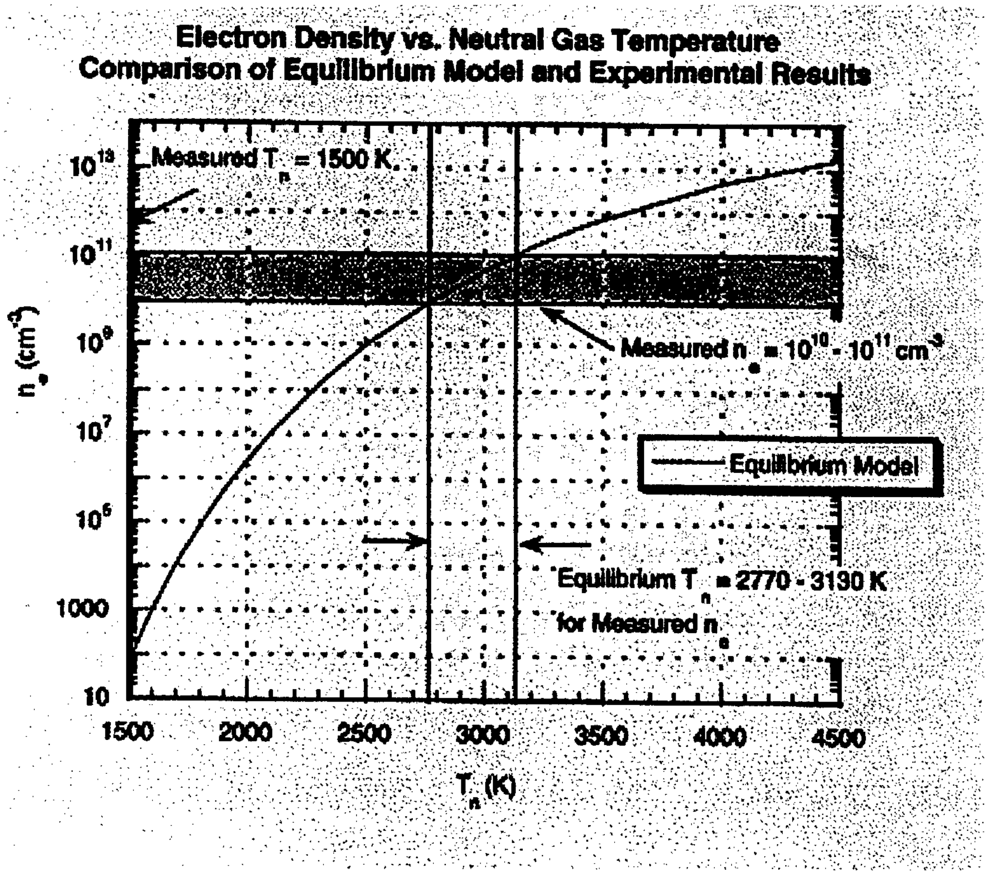


Figure 2.13 Electron density predicted versus measured for various temperatures.

Thus PIA plasma could be made and studied easily, under a variety of conditions, in an ordinary microwave oven. It was found to be a fair conductor, to be high temperature, and to have high than expected ionization levels.

Chapter 3
PIA Plasmas created in Resonant Cavities

Initial attempts at creating PIA plasmas were encouraged by the success of electrodeless, vortex stabilized, microwave gas discharges used in the MET(Microwave-Electro-Thermal) thruster program at RSI. This program used 2.45GHz and also 7.5GHz to create electrodeless discharges in resonant chambers to heat gas for space propulsion. The ease with which these discharges could be made and sustained , along with the work of Powell and Finkelstein (2) suggested that air plasmas could be made and sustained fairly easily. After the PIA plasma state was made using a simple nonresonant microwave chamber with a field enhancer, we returned to the resonant electrodeless discharge to attempt to get rid of the field enhancer, which we felt would lead to impurities in the plasma, and thus limit its lifetime. Such a MET cavity is shown in Figure 3.1.

Vortex stabilized, low order mode cavities were run successfully at both 2.45 GHz and 0.915 GHz, in both TM_{011} and TM_{012} modes. The TM_{012} mode is of particular interest because it creates a plasma on the axis of a cylindrical cavity at the cavity mid-plane, thus allowing complete isolation of the discharge from any solid surfaces or electrodes. The TM_{012} mode is similar to the TM_{011} mode and can be excited in resonators that are only slightly different from those that support TM_{011}. The conditions for resonance , without plasmas, in a cylindrical cavity (12) for 2.45 GHz microwaves are:

$$TM_{011} : \quad c \cdot (x_{01}{}^2/R + \_^2/d^2)^{1/2} = 2.45 \cdot 10^9 \ sec^{-1}$$

$$TM_{012} : \quad c \cdot (x_{01}{}^2/R^2 + 4\_^2/d^2)^{1/2} = 2.45 \cdot 10^9 \ sec^{-1},$$

where c is the speed of light, R is the cylinder radius, d is its length, and $x_{01} = 5.520$ is the first zero of Bessel function $J_o(x)$. For the same value of R in the TM_{012} mode, the length d must be twice that used for TM_{011}. The 2.45GHz cavity optimized for plasmas measured 5cm in radius and 17.2cm in length.

The fact that MET discharges can be run in resonant chambers at both 2.45 GHz and 0.915 GHz (13)is important for creating plasmas of larger size. The creation of large plasmas via the MET technique requires the use of microwaves of wavelength close to the plasma diameter that is desired. For a given mode, the size of the region of most intense electric field, which in turn helps determine the plasma size, scales linearly with the wavelength of the microwaves. In the MET at 2.45 GHz, nitrogen plasma spheres appear to be 3 cm, or 1/4 wavelength in radius. The plasma size for a 0.915 GHz discharge in the same mode should therefore be approximately 9 cm in radius. The plasma radius also appears to vary with power level and vortex velocity, with higher powers leading to larger plasmas and higher vorticity to smaller and more elongated plasmas.

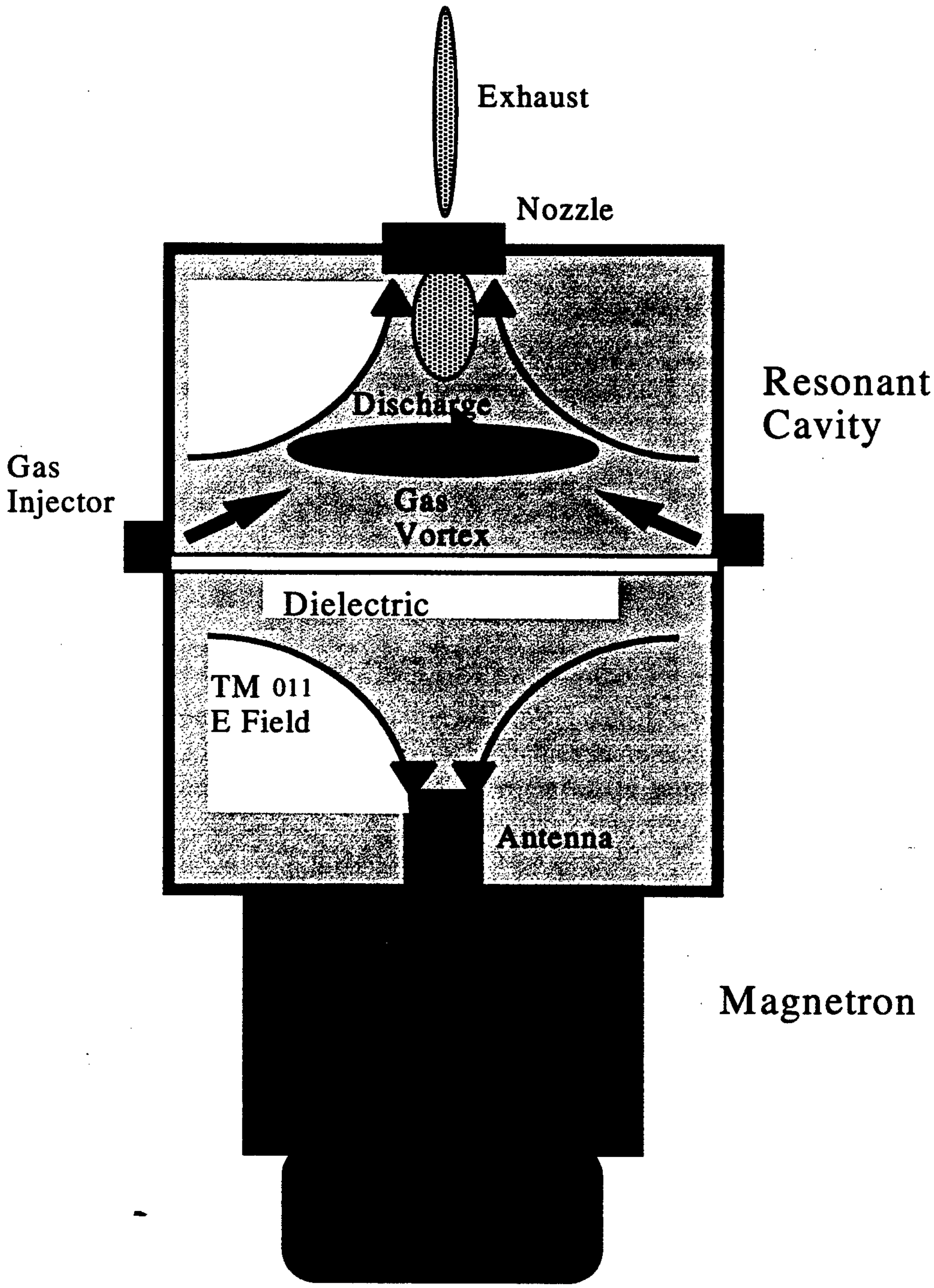


Figure 3.1 The MET, a cylndrical microwave resonator, with an electrodeless discharge , that can be directly driven by a microwave source.

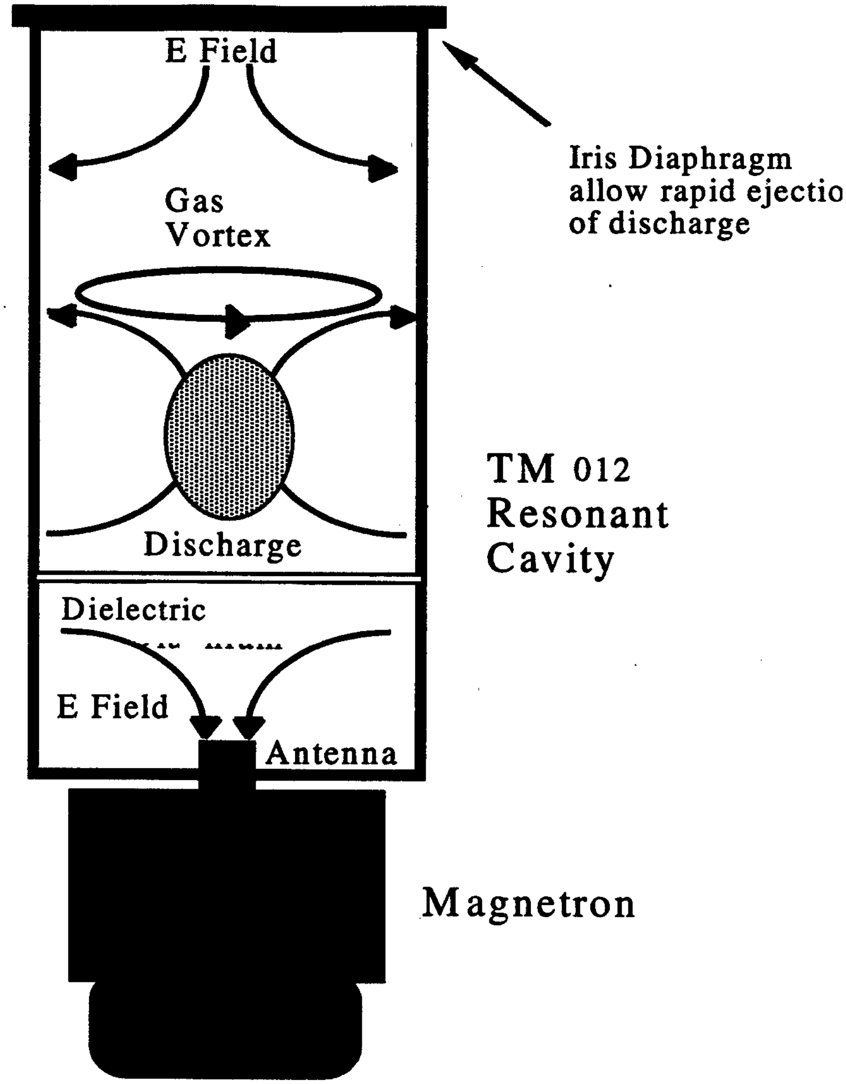


Figure 3.2 A TM012 mode MET type cavity for creating isolated discharges. A removable cover can be added to allow rapid ejection of the plasma from the cavity.

By this logic, lower frequencies than 0.915 GHz would yield even larger plasmas but the approach of using resonant chambers would become difficult because of their larger size.

Laser and Electrodeless Ignition of PIA

Our initial attempts at making PIA plasmas by transferring an electrodeless discharge from a 2.45GHz resonant chamber to a nonresonant chamber were unsuccessful. Later attempts using 7.5GHz discharges in a resonant chamber that was separated from the resonant chamber by an a iris diaphragm were also unsuccessful in transferring the discharge into the 2.45GHz field. Both of these attempts were part of an effort made to create entirely electrodeless systems, that would not need a sharp field enhancer. In both cases, 2.45 and 7.5GHz , small electrodeless discharges were created and allowed to rise into 2.45 nonresonant cavity fields, however, in both cases these discharges went out , despite the presence of the 2.45 GHz field. This technique may be revisited later, but appeared inexplicably difficult.

Therefore we abandoned this technique and returned to the tried and true, if somewhat crude looking, sharp point plus sparkplug system for creating PIA plasma.

This lack of success in transferring electrodeless discharges from a resonant to nonresonant cavity did not dampen our desire to ignite electrodeless discharges in resonant cavities themselves. We felt that this technique would form a very useful technology for using the resonant cavity as a plasma source in the atmosphere at low pressure or in preparing electrodeless discharge for study of air plasmas.
Success was achieved in igniting plasmas in a nonresonant cavity (microwave oven) using laser induced breakdown in the air as a UV source, and allowed elimination of the sparkplug. Further, in a resonant cavity laser breakdown ignition in midair was used to create a PIA plasma in heavy argon-air mixtures, without any requirement for a sharp-pointed field enhancer. The laser used in both resonant and nonresonant cases was a repetitive pulsed Neodymium YAG laser of 10mJ per pulse. This was achieved at the High Energy Laser Laboratory at Penn State, through their gracious cooperation. Thus the principle of laser induced breakdown was demonstrated to allow ignition of PIA plasmas. This was demonstrated under favorable circumstances of high field and high argon enrichment. Higher power drivers for such cavities could probably allow elimination of argon. The success of this technique was discussed with other researchers in the air plasma effort and has been adopted by workers at Princeton University. A diagram of this technique is shown in Figure 3.3 below.

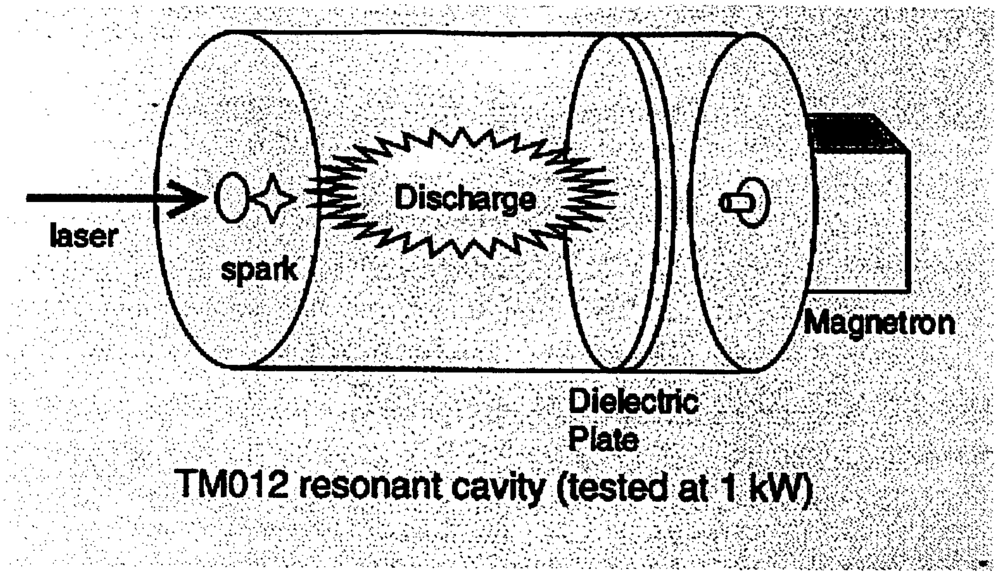


Figure 3.3 A diagram of a successful scheme for igniting electrodeless plasmas in a resonant cavity. Cavity had to oriented horizontally to prevent plasma from moving due to thermal convection.

915MHz Vortex Stabilized Plasmas

Drawing on the success of the 2.45GHz plasmas created in resonant cavities, it was decided to attempt this using 915MHz industrial heating microwaves. A new cylindrical cavity was designed and built based on 2.45/.915 = 2.68 scaling from the successful 2.45GHz cavity, and thus used a cylinder of 46 cm length and 13.4cm radius . The use of 915MHz was desirable because it is available at very high powers, and, because plasma size in a resonator appears controlled by wavelength, the 915MHz plasma would be expected to be larger.

Through the kind cooperation of Scott Best of DuPont Research Laboratories in Willmington Delaware, who allowed us access to their 915MHz generator facility, we were able to ignite and sustain a 915MHz , vortex stabilized discharge running on air both at low pressure and under high pressure. It was observed that under low pressure the air plasma created large amounts of a reddish brown gas which filled the fume hood, this gas has been tentatively identified as NO_2 and would be quite toxic. The plasma was observed to form at 30-50kW but not below this. It could be ignited by either inserting a tungsten rod into the nozzle to create a field enhancement, or, by lowering the pressure in the resonator to a few Torr , to allow easy breakdown, followed by a slow raising of the gas flow rate and thus chamber pressure. The plasmas were observed be similar to those seen in 2.45 GHz resonators , except that they were larger in dimension by roughly a factor of three.

A image of the resonator mounted on the microwave waveguide leading to the 915MHz generator is shown in Figure 3.4, and a view of the resonator with an air plasma visible inside the chamber and exiting through the nozzle is shown in Figure 3.5 .

Therefore, the vortex stabilized plasma could form the basis for an entirely electrodeless system for creating PIA plasmas , and the vortex stabilized technique of sustaining PIA plasmas in air can be scaled to 915MHz , a fact that encouraged our efforts to create PIA plasma in a large nonresonant cavity.

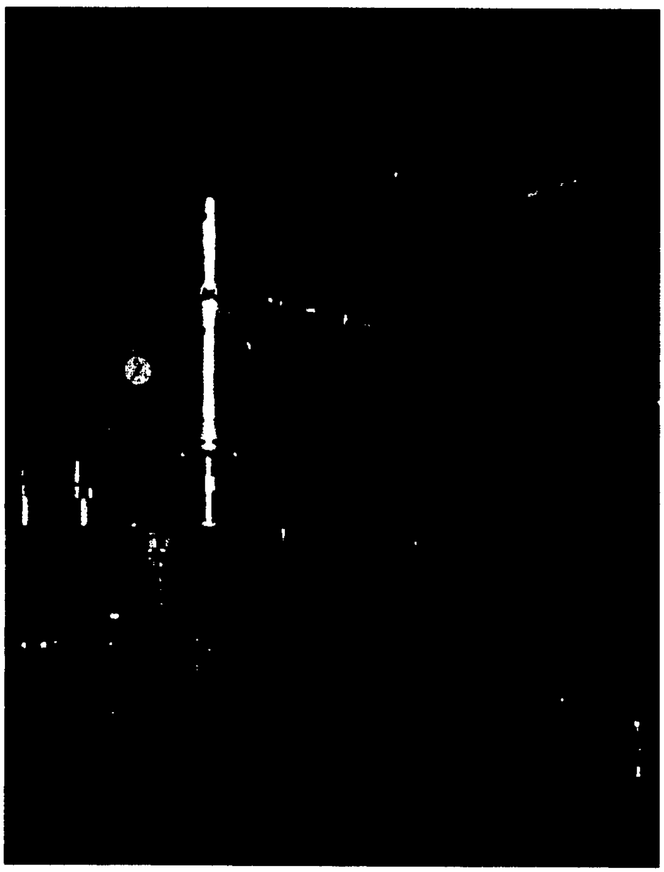


Figure 3.4 A 915MHz cylindrical resonant cavity mounted on a high power waveguide from a 50kW 915MHz generator. Image courtesy of DuPont Inc.

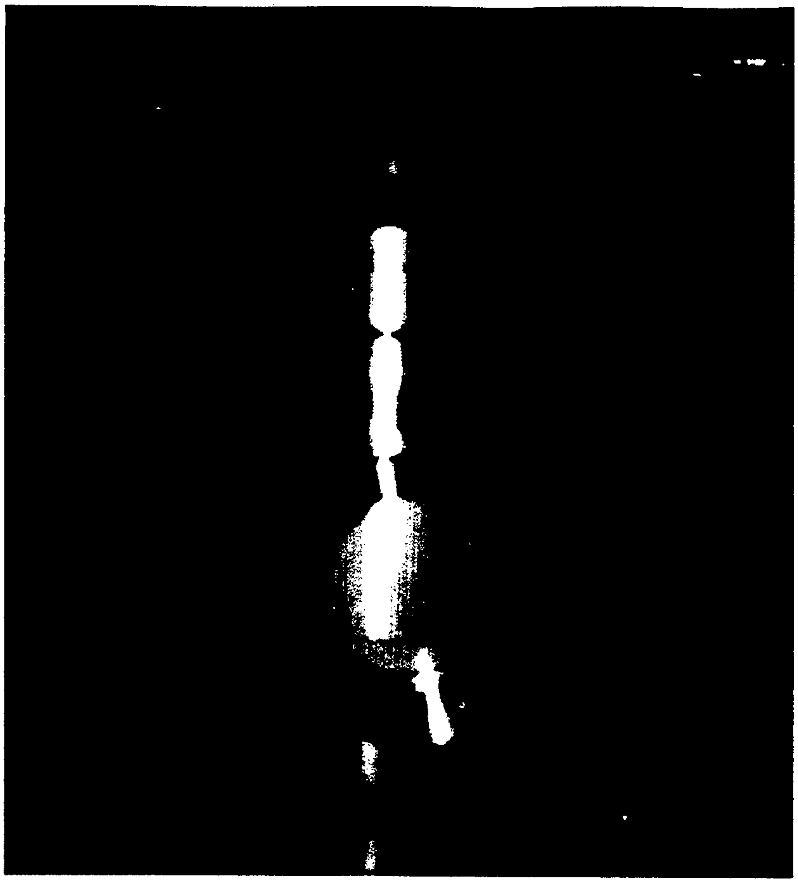


Figure 3.5 A vortex stabilized 915MHz driven air discharge in a resonant cavity. Note plasma jet emerging from the top.

Chapter 4

Scaling of PIA Plasmas in Nonresonant Cavities to 915 MHz

Scaling experiments

The goal of this portion of our investigation was to characterize the properties of microwave-driven persistent ionization in air (PIA) discharges in nonresonant cavities using 915MHz microwaves. The exploration of 915MHz microwaves for generating PIA plasmas was motivated primarily by the desire to make large PIA plasmas at high power. For several reasons 915MHz is ideal for such large scale applications: the size of the PIA plasmas produces appeared, under some circumstances , to be controlled by the microwave wavelength, thus 915MHz , being 2.7 times longer in wavelength would test scaling to larger size, in addition 915MHz can be generated at high power, 100kW- 1MW at very high electrical efficiency, 90-95% making it ideal for large scale applications involving simple generators. Experiments at 915 MHz , in both resonant and nonresonant cavities, were very successful and demonstrated that PIA plasmas could be made in larger size than those at 2.45 and also at higher power, 30-50kW with the steady state value of ~ $1MW/m^3$ being preserved. The PIA plasmas created produced large amounts of ultraviolet light which produced mild "welders sunburn" on the faces of two experimenters, who were also wearing protective goggles. Therefore, high power experiments with PIA can be quite dangerous.

Previous data have been collected from a 2.45 GHz, 1 kW discharge. This experiment used both a 1 kW discharge and a 915 MHz, 30-50 kW discharge. Data included a Langmuir probe, high-speed video, and color video for the 915 MHz discharge, and spectral emissions for both the 915 MHz and the 2.45 GHz discharges. The PIA plasma appeared to be of essentially the same character as the low power versions but was more strongly driven and was perhaps more like a conventional arc.

Materials and Methods:

The new 915 MHz untuned cavity was scaled with wavelength from the high-frequency design. Using the 2.45Ghz microwave oven as a guide to the design of a nonresonant cavity, the dimensions of a microwave oven were scaled upward by the factor of 2.45/.915 =2.7 Starting then with a 40 cm tall, 57 cm wide, and 59 cm deep kitchen microwave oven cavity we obtained a chamber 1 meter tall, 1.5 meter wide and 1.5 meter deep. It consisted of a steel box of 1/8 inch thick steel with welded seams and three access ports. An earlier version with unwelded seams had suffered arcing and was thus considered unsafe. One port was designed to accommodate a standard 915 MHz waveguide flange from the power source. Another flange contained the Langmuir probe insertion port, UV source, adjustable field enhancement spike, and argon feed-through. The last flange had a metal grate for an optical viewport. This port was used to insert a 3" diameter, 5.5" long borosilicate glass cylinder to confine the discharge for data analysis.

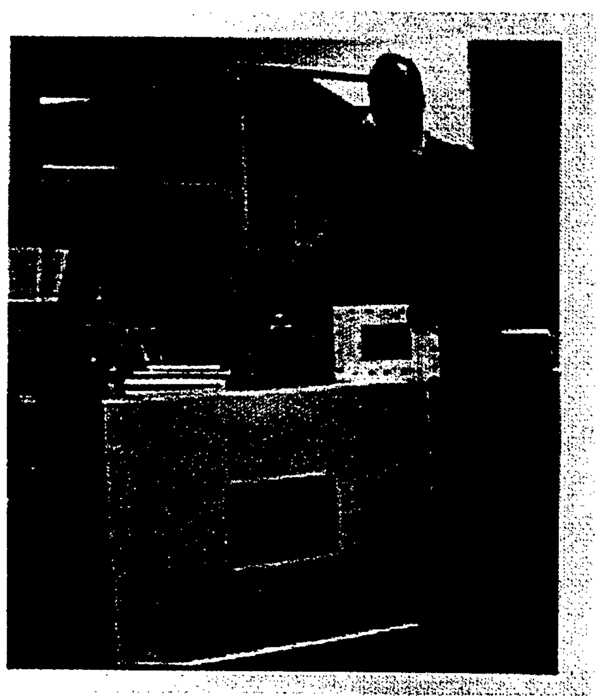


Figure 3.1 "the Doghouse" used for 915MHz PIA plasma scaling experiments. Observation grate has been removed and is displayed above the chamber along with baseplate.

The Langmuir probe system was designed to avoid damage to the probe by prolonged exposure to a high-power discharge. The probe itself was a solid brass rod with a tungsten section actually exposed to the discharge, insulated by a borosilicate tube, then shielded by a brass tube. The shield tube was also insulated from the discharge by an additional layer of borosilicate glass. The probe was injected using a motor and gear assembly. It entered the microwave chamber for approximately a half-second before retracting. While the probe was immersed in the discharge, a voltage sweep from -10 V to +10 V was applied to it, and the current drawn from the discharge was measured on an oscilloscope.

The color video system consisted of an NTSC color camera that viewed the optical access port. The video was recorded by the autofocus camera on VHS videotape, and then digitized afterwards on a frame-by-frame basis. The goal was to provide information on the spatial extent, motion, and general optical emission of the discharge.

The high-speed video system was a microsecond shutter CCD camera viewing the optical port. A 75 mm, 2.8 f-stop lens was focused on the discharge at a distance of 1m. The video was recorded digitally using a computer video acquisition card. This limited the frame rate to 20 Hz at a resolution of 160 x 120 pixels.

The spectroscopy was performed using a spectrograph that covered 80 nm. A greyscale, 30 Hz CCD camera measured the output from the spectrograph. The camera incorporated a 28 mm 2.8 f-stop lens, focused on the exit image plane of the spectrograph at a distance of 8". The discharge emissions were imaged on the 10 micron entrance slit of the spectrograph using a planoconvex lens. The lens focal length was 27 cm for the high-power experiment, and 14 cm for the low-power test. For the high-power test, the spectrograph output was recorded digitally at a 20 Hz frame rate at 160 x 120 pixels resolution, corresponding to a 0.8 nm per pixel resolution. For the low-power test, the output was recorded at 30 Hz on VHS tape, and then digitized on a frame-by-frame basis afterwards at 640 x 480 pixels resolution, providing a 0.2 nm per pixel resolution. Calibration was performed using a mercury-argon discharge lamp. For the high-power test, the lamp was located at the entrance slit of the spectrometer due to the inaccessibility of the discharge location. The low-power test calibration lamp was placed at the discharge location. The spectrograph grating was set for a 505-585 nm range for the high-power test, and for a 525-605 nm range for the low-power test. The digitized data were then measured using a digital densitometry technique. The pixels values across the aperture were plotted to provide spectra.

Results and Conclusions:

The proof-of-principle of the high-power 915MHz, nonresonant system was very successful; large-volume discharges were formed in argon-air mixtures at power levels from 30-50 kW. This effort was done with the great cooperation of Ferrite Components Inc. of New

Hampshire, which specilizes in the manufacture and optimization of 915MHz microwave systems for industry. We performed this research at their facility in Nashua New Hampshire.

Ignition of the plasma was slightly more difficult than in the 2.45Ghz case , principally because the larger size of the apparatus made the UV source marginal, since it was more difficult to scale. Ignition was begun finally, by using a brass scouring pad, which caused immediate and spectacular breakdown. Ferrite Components personnel informed us that air plasmas of the type we were creating were often created by accident in their development programs, and were considered a serious hazard.

The color video showed large volume, hemispherical discharges rising through the air and contained in the dielectric vessel. The discharges filled the 0.6 liter vessel, but would leak out through openings in the sides of the vessel and grow to 4 liters size or larger as they rose through the air and headed towards the microwave source. The cameras had restricted views of the cavity, so both the extent of the discharges as they grew and the persistence after power shut-off were not measured. The colors appeared similar to those observed in the low-power discharges, including red, blue, and purple emissions. A frame from the digitized video is shown below. The discharge can be seen contained in the glass vessel, but it is in the process of escaping out the right side of the vessel through a crack, and forms a hemisphere as it rises in later frames. Inside the vessel, filamentary discharges can be seen within the main structure. Suggestions of current loops can be seen moving within the main discharge.

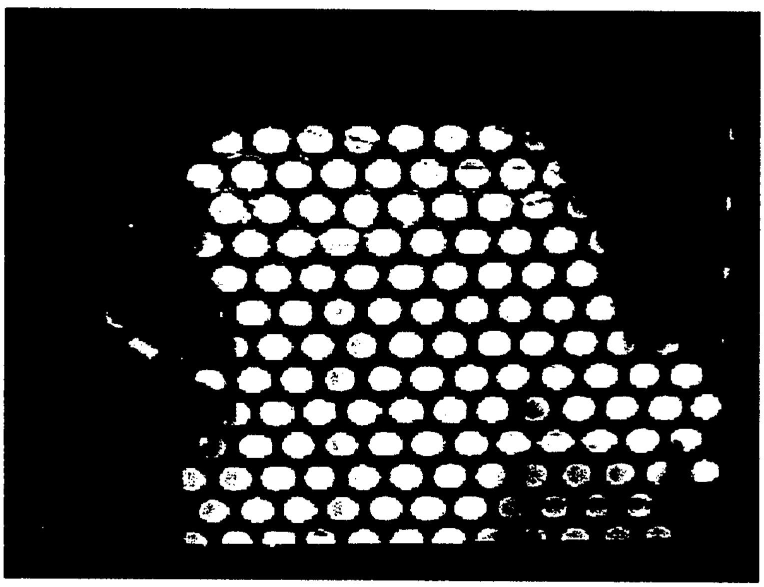


Figure 3.2 A video frame (16 msec exposure) of a PIA plasma rising past the observation grate. Note irregular and filamentary structure.

The high-speed CCD camera provided information on discharge structure. It was operated at a 10 microsecond shutter speed. A frame is shown below, which occurs after a discharge escapes from the dielectric vessel. The hemispherical structure can be seen. The high-

speed video appears to indicate that the discharges have solid walls, but hollow interiors. Loop discharges were also visible in some frames.

Figure 3.3 A high speed framing camera image (10μsec exposure) of a PIA plasma generated by 915MHz.

Size of the coherent PIA plasma blobs was estimated by the image size on the CCD of the video camera, as shown in Figure 3.4. The geometric optics problem leads to the equation:

$$diameter \quad of \quad PIA = S2 = \frac{S1}{L1} L2 \cong 30 \ cm$$

Where S1 is the CCD width = 1cm , L1 is the focal length of the video camera optics, 10cm, and L2 is the distance to the PIA plasma 3meters. The diameter of 30cm means an approximate volume of 14 liters, meaning that a 30kW of input power in microwaves, that the scaling of ~ 1W/cc or 1 MW /m^3 scaling is preserved from small scale plasmas. Thus it appears possible to make PIA plasmas of as large a size as desirable.

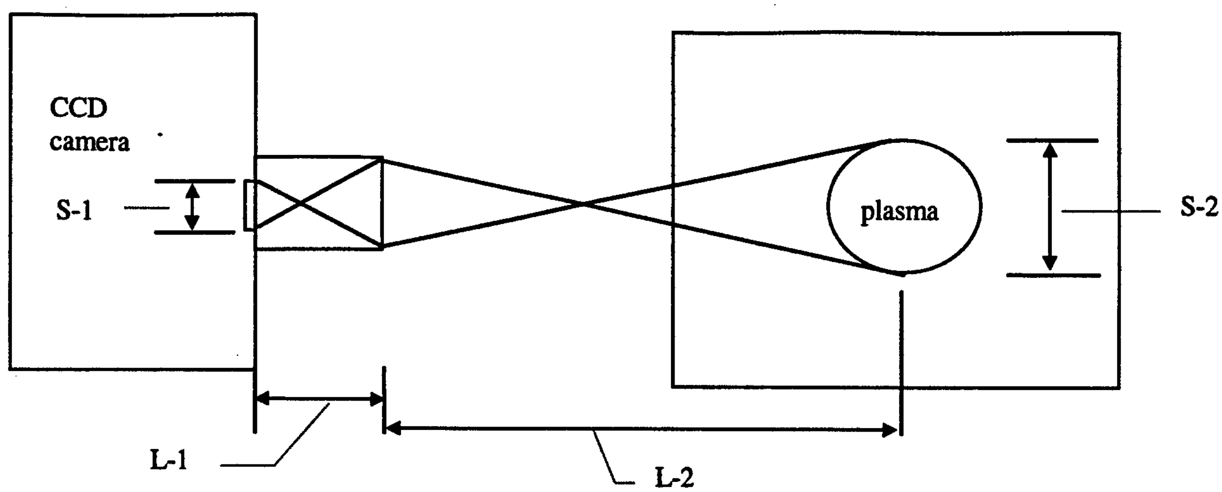


Figure 3.4 Geometric optics problem used to estimate size of PIA plasma in 915MHz experiment.

Images of frame by frame dynamics of the PIA plasmas created in the 915 MHz experiment are shown in Figure 3.5 and 3.6, with an incoherent filamentary structure seen in Figure 3.5 and a large coherent mass seen in Figure 3.6.

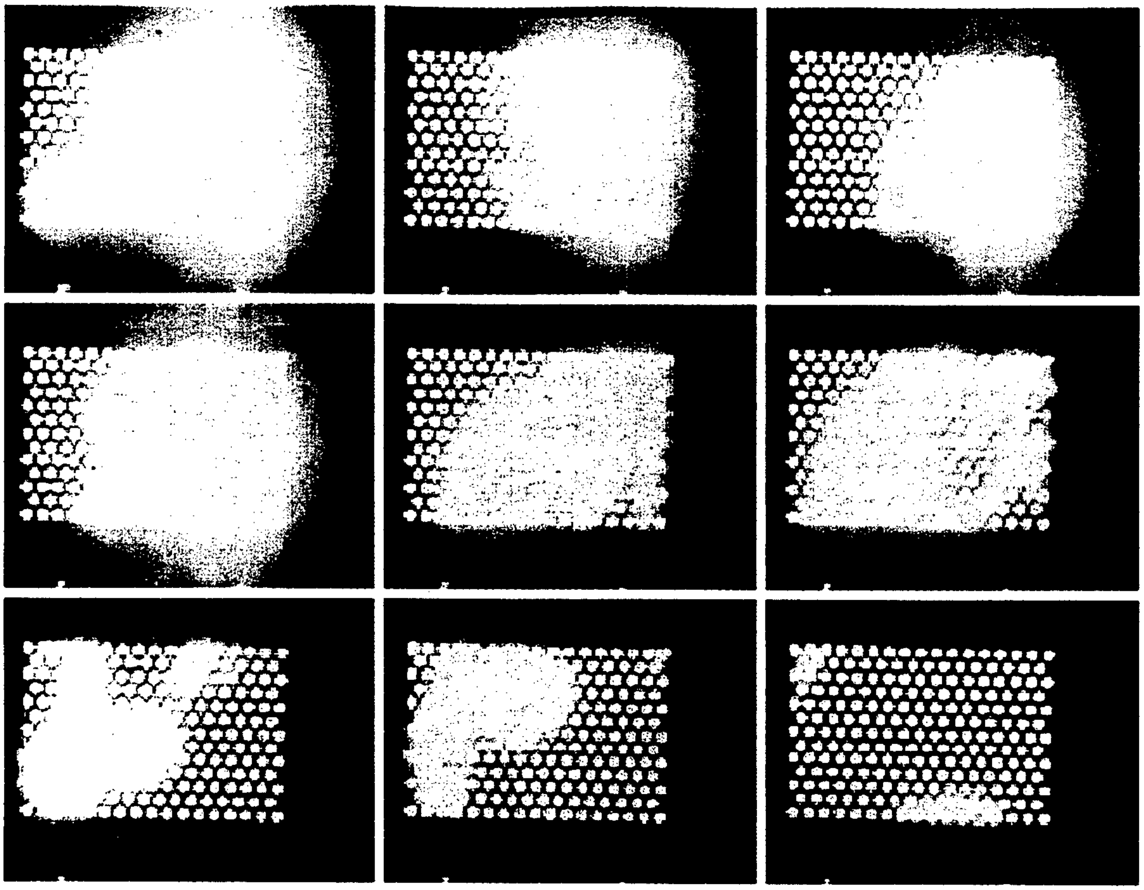


Figure 3.5 A large filamentary PIA plasma seen riseing on videotape frames, as viewed through the doghouse grating.

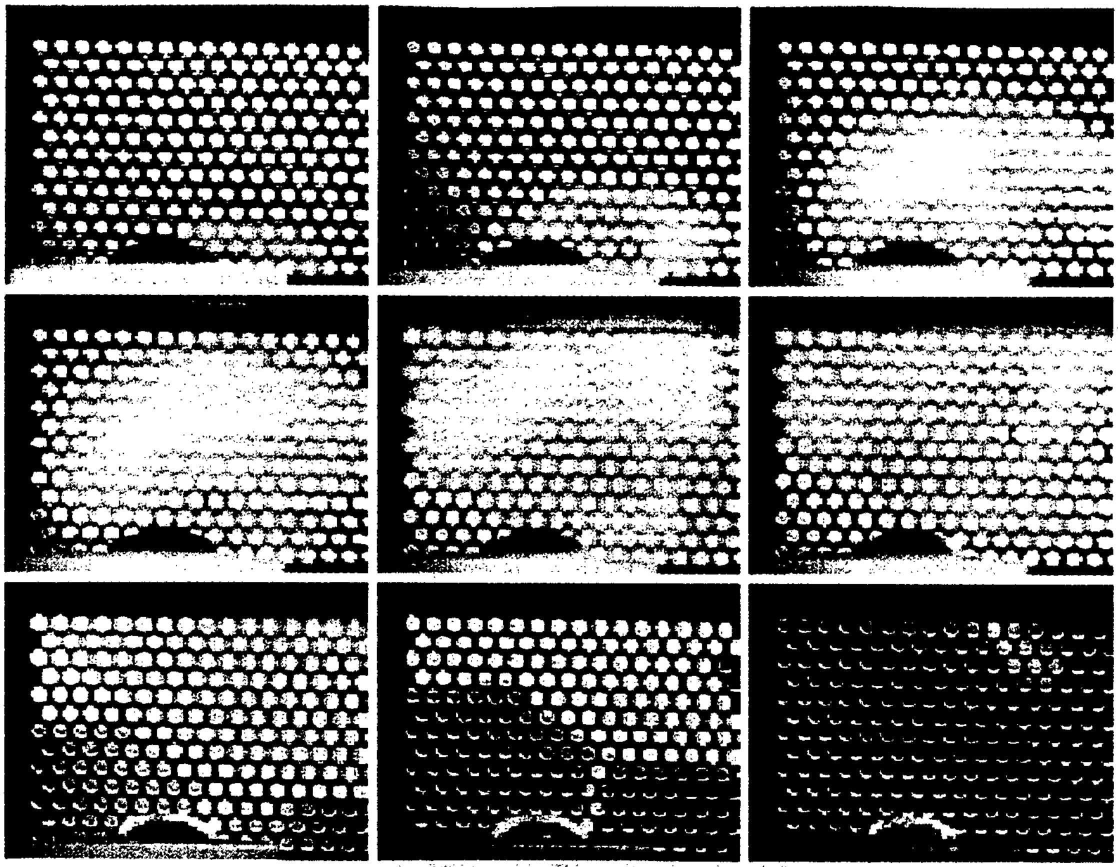
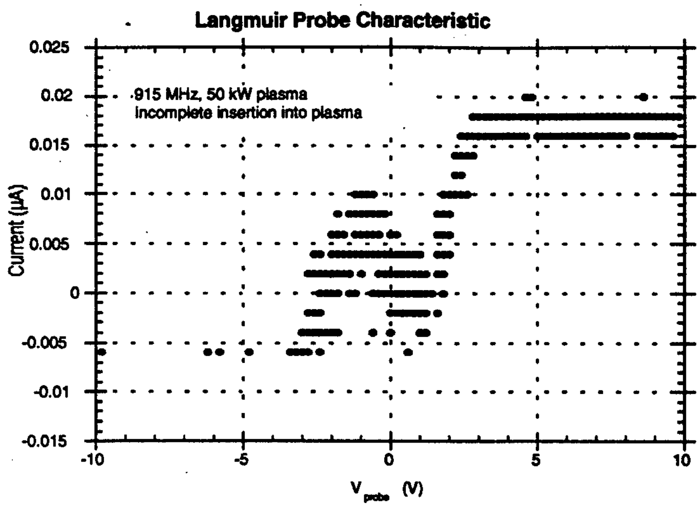


Figure 3.6 A large spheroidal PIA plasma seen rising on videotape frames, as viewed through the doghouse grating.

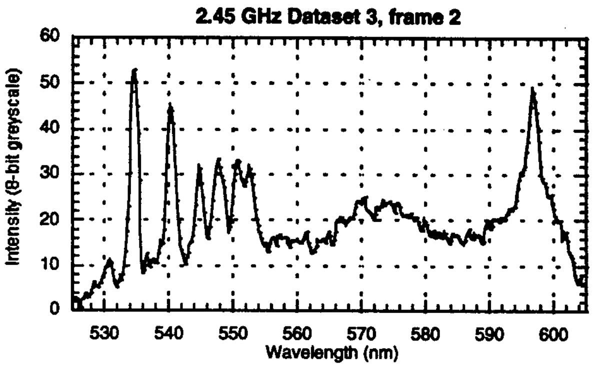
Problems were encountered in triggering the Langmuir probe system. The trigger for the mechanical insertion was not coupled with the voltage sweep or oscilloscope trace, which resulted in only one dataset being acquired when the probe was inserted into the discharge. Unfortunately, even during that dataset, the probe only partially inserted, so the electron density measurement was low by several orders of magnitude. The data are shown in the figure below.



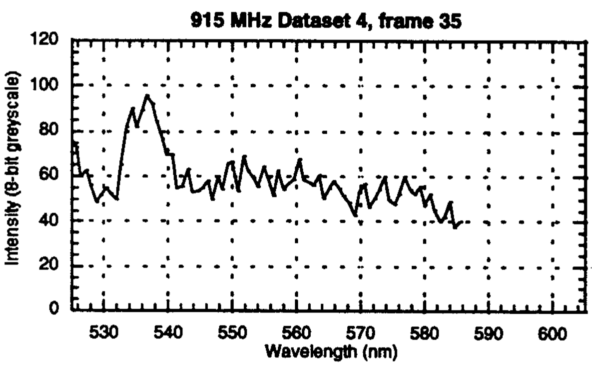
The assumption was made that normal Langmuir probe theory could be used; however, given the high pressure in the system, collisionless models were most likely inadequate. A plot of ln (probe current) vs. Probe voltage provided electron temperature, assuming a Boltzmann distribution of temperature. This provided an electron temperature of 1.0 eV +/- 0.3 eV. This was used together with the ion saturation current to determine an electron density, but the value obtained, 10^4 cm^{-3}, was several orders of magnitude too low compared to the value of 10^{10} cm^{-3} obtained with a low-power discharge using a fully-inserted, stationary probe. It does indicate an axial variation in electron density, but much more data are needed to determine the axial profile, and more importantly, the value at the center of the discharge. In addition, collisionality of the discharge must be taken into account for a proper analysis of Langmuir probe data.

The spectral emissions data were coarse for the high-power experiment, but appeared to match those obtained from low-power discharges. In both cases, information was obtained on the dynamic behavior of the spectra. In the high-power experiment, as the power was shut off, some lines were observed to diminish in amplitude, while others increased for a short time. Unfortunately, the coarse resolution made identification of the high-power emission lines difficult. The low-power lines were easier to resolve with the 640 x 480 pixel images. Lines were found in almost all low-power datasets at 530.7 nm, 534.6 nm, 540.4 nm, 544.9 nm, 547.8 nm, 550.8 nm, 552.4 nm, and 596.7 nm. Width of the lines was consistent between datasets, and variation in amplitude could be seen as the discharges dimmed on the 40 ms timescale of the CCD data. Two datasets showed different dominant lines, at 528.4 nm and 555.2 nm. It is possible that those datasets only included the spark discharge of the UV source (it produced visible light as well as UV), and not the emission of the glow discharge. The 530.7 nm, 534.6 nm, 540.4 nm, and 550.8 nm lines could be seen in the high-power datasets, but the resolution was too low to reliably identify the lines as being the same. A low-power frame is shown below, along with the line plot. Afterwards, a line plot of a high-power frame is shown for comparison. The low-power lines were very consistent from shot to shot in both location and width, and the line amplitude correlated with the overall brightness of the discharge.

a.



b.



c.

Figure 3.7a,b,c. Spectral data from a. and b. a 2.45 GHz ,1kW PIA plasma, and c. a 915MHz 30kW plasma.

Identification of the low-power lines is possible; their resolution is 0.2 nm, which is sufficient to compare with reference data on constituent species. Given the large number of species that were in the experiment, however, it is difficult. A look through prominent lines for atomic argon, nitrogen, zinc, and aluminum did not find any at the values given above. There is an atomic oxygen line (Oxygen I) at 533.7 nm that is very prominent, close to the 534.6 nm value above, but not within the spectral resolution. There is a strong copper line at 529.3 nm, but again, this is not too close to an identified line. Iron I lines at 532.8 nm, 534.1 nm, and a carbon I line at 538.0 nm are other possible, but still not matching, candidates. An iron I line at 540.5 nm

could be the 540.4 nm line found. The field enhancer, a sharp metal point, contained iron, among other metals, in both experiments, and iron oxide has been found coating the dielectric vessels after both high- and low-power experiments.

A comparison of spectra between the 915 MHz and 2.45 GHz plasma indicates that the 915 plasma was dominated by continuum radiation and bands rather than lines, indicating a somewhat higher temperature. The plasmas were probably more strongly driven in the 915 MHz case, since their volume per unit of microwave power was less.

Future Work:

A close look at emissions of molecular nitrogen and oxygen could provide identification of the other lines. Full identification, even if tentative, should be made of all emission species. A monochrometer arrangement would provide much better spectral resolution, but would limit scanning to one line. This could lead to an understanding of pressure broadening effects or even of the mechanism for prolonged discharge lifetime.

Redesign of various diagnostics would help greatly in future experiments. The mechanical probe system has already been coupled to the voltage sweep and oscilloscope trace, so future Langmuir probe data should be of fully immersed probes, which should indicate the extent of collisionality effects on electron density measurements. It may be necessary to use microwave interferometry to determine densities, though again, collisionality may interfere. The method used in the low-power experiment, of recording the CCD data on videotape and then later digitizing at high resolution, should be used for high-speed imaging and high-power spectral data in the future.

Redesign of the high-power cavity will include easier access using a microwave-sealed door, better optical viewing with a larger viewing grate, and better protection of the microwave source to avoid damage from discharges. A second high power test is planned for Summer 1998. Preparatory low-power experiments will incorporate the changes in the Langmuir probe and high-speed imaging systems, and should provide good tests of the diagnostics before the high-power experiment. The end result will be a solid body of spectral, Langmuir probe, and video data of both high-power and low-power PIA discharges.

Therefore, the phenomenon of PIA plasmas has been found to be scalable to 915MHz and higher powers with its properties essentially unchanged from that produced at 2.45GHz .

Chapter 5

Discussion and Summary

Therefore, we have attacked a problem many outside AFOSR thought impossible to solve , and have solved it. Large plasmas can be made and sustained at low power density, on the order of 1 MW/m^3, these plasmas can be scaled to tens of liters in volume at 75kW using 915MHz or created within an inexpensive microwave oven at 1KW using 2.45GHz. The PIA plasma created is hot , at 4000K as hot as a combustion flame of hydrogen and flourine , the hottest combustion known, yet relatively cool compared to an arc plasma. Its conductivity is roughly comparable to a semiconductor germanium at approximately 1mho-m.. Its inferred electron density is approximately $n_e = 10^{12} - 10^{13}$ depending on the effective collision rate. The plasma appears to persist for at least 200ms after power cutoff. Accordingly, the PIA hypothesis appears to be supported.

The duration of the PIA discharges after power cutoff at atmospheric pressure is hypothesized to be caused by long-lived metastable states of some air molecules. This explanation was favored by Powell and Finkelstein (2) and has much to recommend it. Long-lived metastable states of nitrogen are well known to cause afterglows in chambers after electric discharges. However such states are usually seen only at low density , were collisions with other molecules will not quench them. The singlet ^1S state of atomic oxygen however, is not quenched by collisions with air molecules, so the existence of metastable states that can store energy and also drive other processes such as ionization in a gas is not in dispute. At this point in our research this explanation appears most reasonable for the PIA. In nature the 200ms lifetime of PIA plasma may be augmented by the existence of excess charge on an isolated mass of PIA plasma. Such an excess charge may serve as an energy store for a PIA plasma blob that allows its regeneration by ionizing air at its surface until enough charge leaks away, and it then would decay with the usual 200ms timescale. . An experiment to prepare PIA plasma in a microwave enclosure , that was the top electrode of fully charged a Van de Graff generator , and then release it through the of the electrode, would test this hypothesis.

Some theoretical other models have been proposed for ball lightning that suggest the involvement of RF waves. A recent model (14) uses the concept of an electromagnetic knot, with tangled magnetic fluxes, for such plasmas. The turbulent behavior seen in our experimental plasma suggests that magnetic fluxes may in fact be entrained and amplified in the plasmas. However, the expansion of the plasma as it cooled, predicted in the knot model in the case of infinite conductivity, was not observed in our experiments. This may be due to the finite conductivity of the plasma and not a deficiency of the basic knot model. An earlier concept (15) considers ball lightning as an evacuated microwave resonant cavity surrounded by a layer of plasma. In this experiment, however, very little microwave radiation was coupled out of the ball by the probe. Another theory (16) considers that vorticity may play a part. This would appear to be the case, at least in our experiments, as the plasmas were observed form reproducibly in the presence of mild vorticity and, once formed, to rotate quite turbulently inside the Plexiglas tube. This can be partially explained by the fact that in the core of a vortex ,pressure, and thus gas density, is lower than elsewhere in the flow field and thus increases the important breakdown parameter E/P , allowing gas breakdown to occur and persist more easily. Thus a vortex core will preferentially breakdown. Thus , it is not surprising that the most intense portion in the core of the PIA plasmas appeared to have the form of a toroid, which is the natural shape of a localized vortex.

Summary

Therefore supported by AFOSR, and encouraged and helped by the other members of the MURI and Plasma Ramparts effort, we were able to prepare and study large plasmas made out of air at full atmosphere, at low power density , approximately 1W/cc , and to do this with simple and inexpensive apparatus. Further, we have now demonstrated that this plasma can be scaled to larger size and higher power, using microwave sources that are widely available commercially. These techniques and apparatus we have freely published (17) and shared with the community and we have eagerly sought collaboration and efficient use of resources within our community. We have been rewarded for this effort by much help from Stanford and Ohio State and others, and as a result of this collaboration we have achieved a much greater success and understanding of the PIA plasma phenomenon. It is our anticipation that the techniques we have developed, using nonresonant microwave cavities (microwave ovens) with 2.45GHz and 915MHz microwaves, will be adopted widely and that PIA plasma will eventually become a staple of air plasma research.

This research has confirmed the PIA hypothesis, that a means of ionization in room air exists that is long lived, approximately 200ms duration, as is suggested by thunderstorm phenomenon , and that this allows persistent ionization in air, and also sustained plasmas at low power. This research effort has been a great pleasure , especially since at the beginning of this AFOSR effort the consensus of the wider plasma community viewed large "room" air plasmas at low power density as technically impossible. We have shown this not to be the case, and we have the sunburns to prove it.

Acknowledgments

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